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PRELIMINARY INVESTIGATION OF COKE AS A FILTER MEDIA IN WATER TREATMENT

by

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ABSTRACT

Filtration is a water treatment process. Higher efficiency in filtration includes longer filter runs with good quality of effluent, higher rates of flow through the filter and less volume of treated water for filter washing. The type of filter media is an important consideration in filtration. Sand has been the predominant filter media.

The object of this investigation was to determine if coke made from coking coal is a suitable filter media and to evaluate its performance by comparison with a sand filter media.

Model filters were constructed and filter tests at various flow rates were made for sand, Michel coke and composite coke filter media.

The coke media was a suitable filter media. It sustained longer filter runs at high rates of flow with a better quality of effluent and lower head losses than sand media. The volume of treated water required for filter washing was less than for sand media.

It is recommended advanced studies be made using coke filters in a complete water treatment that includes coagulation and sedimentation.

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GLOSSARY OF TERMS AND SYMBOLS

Raw Water	–	untreated water from the natural source of supply
Filter Media	–	the solids portion of the material used to separate coagulant floc, turbidity, micro-organisms, and other foreign particles from water by means of filtering action
Composite Media	–	two or more suitable media having different characteristics of size, shape or specific gravity etc.
Filter Wash	–	to reverse the flow of water through the standard rapid filter at such a rate of flow as to cause the media to expand and thus remove from the filter the accumulated suspended matter which was deposited during the filtering portion of the cycle
Effective Size	–	diameter of largest grain of media in the 10% of the sample (by weight) which contains the smallest grains
Uniformity Coefficient	–	the ratio of the size of sieve opening passing 60 percent of the media to the effective size

LIST OF FIGURES (continued)

GLOSSARY OF TERMS AND SYMBOLS (continued)

a = surface area shape factor

A = surface area of grains

b = volume shape factor

c = intercept of expansion characteristic on axis of velocity

C_d = coefficient of drag

d = grain size of the filtering material,

= diameter of pipe in pipe flow,

= geometric mean size of two adjacent sieve openings in a sieve analysis

e = porosity ratio of filter media

e' = porosity ratio of expanded filter media

E = resultant expansion expressed as percent of original depth

f = friction factor in the Darcy - Weisbach equation for pipe flow

f' = friction factor in the Carman - Kozeny equation for filtration

g = constant of acceleration due to gravity

G_s = specific gravity of the filtering material

h = head loss in terms of water column and is the frictional resistance offered by granular materials to the passage of water

H_r = hydraulic radius

k = a constant of pipe flow whose magnitude is 32

L = depth of filter media or length of pipe in pipe flow

L' = depth of expanded filter media

L_t = total depth of stratified bed

L'_t = total depth of expanded stratified bed

m = absolute viscosity

GLOSSARY OF TERMS AND SYMBOLS (continued)

n = kinematic viscosity = $\frac{m}{r}$

N = number of grains in filter bed

θ = grain shape factor in the Carman - Kozeny relationship and has a value of 1 for spheres

p = pressure = h r g

P = fraction by weight of the grains retained between adjacent sieves in a sieve analysis. It is assumed the grains are uniform in size between adjacent sieves.

P' = weight in grams of grains retained between adjacent sieves in a sieve analysis

q = rate of flow

r = mass density of water

r_s = mass density of grains of filter media

R = Reynolds number

S = surface area - volume shape factor and equals 6 for spherical grains

T = water temperature in degrees Fahrenheit

v = approach velocity of the water to the filter media. In pipe flow it is the mean velocity of flow.

v_s = settling velocity of grains of filtering material

V = volume of grains

w = unit increase in velocity divided by corresponding increase of expansion

= $\frac{\Delta v}{\Delta E}$

CHAPTER I

INTRODUCTION

1.1 The natural sources of water supply throughout the world seldom meet the standards of quality required for domestic, commercial and industrial use in the present day. As the standards of living increase throughout the world, the equivalent per capita consumption of water increases and a higher quality of water is generally expected. To meet the increasing demand it may be necessary to use less favorable raw water sources. Adequate treatment of raw water will make it acceptable for most purposes.

1.2 Filtration is a water treatment process. It may be defined as the process of passing water through a suitable filter media in such a manner as to effectively remove the suspended solids from the water. Other treatment processes are usually necessary prior to filtration, however filters and their accessories are the most expensive components of a water treatment plant (Ling, 1962). Along with coagulation and sedimentation, filtration is still an important process in the technique of water treatment. The production of clear and sparkling water requires the use of a filter. Filtration also aids in the removal of color, tastes, odors, iron and manganese (Steel, 1960).

1.3 There are several types of filters in use today. The slow sand filter, which came into use on this continent in the latter part

of the 19th century, is designed to permit water to pass downward by gravity through the filtering medium. The rapid sand filter is also a gravity filter but permits passage of water at a much higher rate of flow, and is generally used after preliminary treatment by coagulation and sedimentation. Pressure filters are similar to rapid filters except that the filter media is contained in a pressure cylinder and the water is passed through the media by pressure rather than by gravity. Composite media may be used in the above-mentioned filters. The diatomite filter is a different type wherein the media is a diatomaceous earth layer or cake supported on a septum. Suspended material is removed from the water as it passes through the diatomite layer.

1.4 Finding a more effective means of filtering water has become increasingly important. The basic filter design has not changed to any great extent through the years. Other materials than sand, notably anthracite and sand, may be used in filters but the use of sand has been predominant since the introduction of the slow sand filter. Longer filter runs with good quality of effluent, higher rates of flow through the filter, less volume of treated water for washing the filters and less maintenance to filter beds are all very desirable. It is quite an economic advantage if filter media of the required quantity and quality can be obtained locally.

1.5 Rapid filters in use today exhibit various flow arrangements and filter media. The standard rapid sand filter design consists of graded sand 24 to 30 inches deep with an effective grain size of 0.4 to

0.7 millimeters and uniformity coefficient 1.5 to 1.8, supported on about 18 inches of graded gravel 3/32 to 2½ inches in diameter. The finest size of gravel is in the top layer of gravel. Washing the filter stratifies the graded sand media so that the fine sand is on top and the coarse sand is adjacent to the gravel. The gravity flow is vertically downward in the filter passing through the finer sand first. A typical two-layer or composite filter bed utilizes a 22 inch coarse anthracite layer of 6 to 18 mesh (U.S. sieve) on top of 8 inches of 30 to 40 mesh sand (Conley and Pitman, 1960). Kerrigan and Polkowski (1965) carried out experimental research using plastic pre-filter media. Plastic spheres of cellulose acetate were selected as the coarse material on top of the sand. Fair (1963) states the time is in sight when one shall be free to employ in future works, and not only in laboratory experimentation as at present, granules synthesized by the developing plastics and ceramics industry. The gravel support layer in many filters is being replaced, all or in part, by various patented systems of tile blocks and porous plates. The contact filter developed and tested in Russia in 1953 - 54 is a combination clarifier and filter, utilizing upward flow through the filter bed (Calise and Homer, 1960). The centred-outlet or bi-flow filter introduces water into a rapid filter at both top and bottom, and filtered water is withdrawn from the center of the filter. This flow arrangement is used to some extent in the Netherlands and Russia (Okun, 1962). The dry filter is used for iron removal wherein water is sprayed on several layers of sand filter successively and is passed through the filter with air in the pores of the sand (Okun, 1962). Another recent development in

Holland and France is an upflow grid filter wherein a grid system of parallel vertical plates located within the bed a few inches from the top serves to prevent expansion of the bed and break through at higher rates of upflow filtration (Smit, 1963). Hudson (1958) has presented evidence that it is not necessary to operate rapid filters at a preset constant rate. Hartung (1957) has demonstrated that filters can be operated satisfactorily and produce a water of high quality without controllers. Although these techniques in the filtration process such as high-rate filtration, variable-rate filtration and uncontrolled filtration have not received complete acceptance in the field of water treatment to date, investigations have been made to determine the effect of changes in filtration rates on filter effluent quality (Cleasby, Williamson and Baumann, 1963; Rogers, 1964).

1.6 In the continuing search for more effective means of filtering water the possibility of using coke, made from coking coal, as a filter media was considered by the Research Council of Alberta. The objective of this investigation was to determine whether coke would be suitable as a filter media and to evaluate its performance in filters in terms of other filter media presently in use.

1.7 To carry out this program of research and conduct a comprehensive experimental review of the many possibilities of coke as a filter media or as included in a composite media, and in the various types of filters with their several flow arrangements, would require several years of time. However, a preliminary investigation could be carried out with the time and facilities available and thus determine in what direction further research should be undertaken. It is believed

the results obtained will be of great value in the interpretation of later studies of actual conditions of filtration and of a more complex nature.

1.8 The slow sand filter was originally considered to be the sole process necessary in water treatment. However, the slow rate of filtration, the large area of filter bed required, the limited ability to reduce soluble color and the method of cleaning the filter bed led to gradual substitution of the rapid sand filter with its usual attendant treatment processes of coagulation and sedimentation. Pressure filtration and diatomite filtration without pretreatment also have limitations when used as the sole treatment process for the clarification of water (Fair and Geyer, 1954; Steel, 1960; Task Group Report, 1965). However, in this coke filter evaluation program it was advanced that the performance of the filtration process only would be suitable criteria for a preliminary investigation. In surface water supplies clays in suspension are generally the most common form of turbidity. The rate of change of head loss through the filter and the measure of turbidity in the filter effluent throughout the filter run, along with wash characteristics are recognized criteria for evaluating filter performance. Model filters were set up using coke as the experimental media, silica sand as the control filter media and a filter influent of constant turbidity. Several rates of flow through the filters were investigated. As secondary investigations an attempt was made to measure the change in concentration of turbidity at intervals of depth throughout the filters and evaluate the sampling procedure from the wall of the filter tube and from the center of the filter bed at the

same horizontal plane. A composite filter media of 3 types of coke was investigated. Each type was of a different specific gravity and grain size such that the stratified filter after washing would be in reverse order in grain size as compared to the standard sand filter.

1.9 Notwithstanding the limitations mentioned in paragraphs 1.7 and 1.8, the control sand filter media made to American Water Works Association specifications for filtering material B100-53 (1953) and typical of the filter media used in water treatment, was tested under identical conditions as the coke filter media and this provided a comparative basis for evaluation.

CHAPTER II

HYDRAULICS OF FILTRATION

2.1 Allen Hazen (1892) derived a formula of an empirical nature applicable to the slow sand filter wherein no stratification occurs, but there is homogenous packing of the sand as the coarse grains are interspersed with fine grains.

$$v = c\, d^2 \frac{h}{L} \frac{T + 10}{60} \qquad (1)$$

In this formula v is the approach velocity in meters per day and d is the effective grain size in millimeters. The value of the coefficient c is dependent upon a number of variables such as sand composition, grain shape, uniformity and compaction of the grains, and ranges in value from approximately 700 to 1000. No method is given for determining its value under given conditions. The hydraulic characteristics of a slow sand filter are different from those of a stratified rapid filter. The temperature of the water T is in degrees Fahrenheit and $\frac{h}{L}$ are the commonly used symbols for loss of head h through the filter media of depth L, due to the frictional resistance offered by the granular media.

2.2 Another early empirical formula related to the slow sand filter was that of Baldwin - Wiseman (1910). It required a determination of the thickness of the water-film retained on the grains of drained sand and also the surface area per unit volume of sand. Both

these requirements were difficult to assess or measure at that time and the formula is seldom mentioned in the literature of today.

2.3 Hydraulics of rapid filter sand was the subject of an experimental investigation by Hulbert and Feben (1933). Their formula for head loss is:

$$h = \frac{24.2}{10^5}\left[\frac{L\ v\ (69.43 - e)}{d^{1.89}\ (T + 20.6)}\right] \quad (2)$$

h = head loss in feet

L = depth of sand in inches

v = velocity of flow in m. g. a. d.

e = porosity (percent void by Jackson turbidity tube method)

d = sand size in millimeters (50 percent or median sieve size)

T = water temperature in degrees Fahrenheit

It is applicable to a sand of any grain shape but is limited in its application to filter media which show void percentages within, or not too far removed from, the limits which hold for the sands used in its derivation. Theoretically the formula indicates a head loss of definite value as the porosity approaches zero, whereas the head loss would actually increase infinitely. With a porosity of 70 percent or more as in coke filter media the head loss would theoretically be zero or of a negative value, which is not true. The investigators state the formula is limited to laminar flow where the head loss is a straight line function of rate-of-flow. The application of the formula requires a sieve analysis of the graded filter sand and determination of its porosity. Both of these can be determined in the laboratory. The total head loss is the sum of the individual head loss calculations for each

separate size fraction of the graded sand as obtained in the sieve analysis.

2.4 A theoretical approach, starting from a dimensional analysis of the streamline flow of water through pipes, led Fair and Hatch (1933) to the formulation of flow characteristics of water through stratified and unstratified sand filter media and through the expanded filter bed. Their theory was in close agreement to their subsequent experimental data. They believed the analogy between pipes and sand beds with streamline flow could be extended into the range of turbulent flow and that their equations may be valid for the passage of gases and liquids other than water through materials other than sand. An analytical derivation for laminar flow in circular tubes was made by Wiedemann in 1856. Hagen in 1839 and Poiseuille in 1840 independently carried out the experimental investigations and confirmed the analytical derivation. Their equation (Streeter, 1951) is as follows:

$$q = \frac{\Delta p \, \pi \, d^4}{128 \, m \, L} \qquad (3)$$

q = rate of flow

Δp = pressure drop (energy loss per unit volume) in length L

d = diameter of tube

L = length of tube

m = absolute viscosity

Fair and Hatch (1933) reduced this type of equation to:

$$\frac{h}{L} = \frac{k \, m \, v}{g \, r \, d^2} \qquad (4)$$

h = head loss in terms of water column

k = a constant of pipe flow whose magnitude is 32

g = acceleration due to gravity

r = mass density of water

v = mean velocity of flow

The equation holds for any consistent system of length, weight (mass) and time. Relating this to a filter bed, L would become the depth of bed and $\frac{v}{e}$ the mean velocity of flow through the channels where v is the velocity of approach over the gross area of sand and e is the porosity ratio. The diameter term was replaced by the hydraulic radius (H_r) as it is used in hydraulics to evaluate what corresponds to the diameter effect of non-circular conduits.

$$H_r = \frac{\text{cross-sectional area of pipe}}{\text{wetted perimeter of pipe}}$$

$$H_r = \frac{\text{area} \times \text{length}}{\text{perimeter} \times \text{length}} = \frac{\text{volume of water}}{\text{surface area of conduit}}$$

$$= \frac{\text{volume of water in sand pores}}{\text{surface area of sand grains}}$$

$$= \frac{\text{volume of voids}}{A}$$

$$= \frac{e \times \text{total volume of filter}}{A}$$

$$= \frac{\frac{e}{1-e}\ (\text{volume of sand grains})}{A} = \frac{V}{A} \times \frac{e}{1-e} \qquad (5)$$

Therefore $$\frac{h}{L} = \frac{k}{g}\,\frac{m}{r}\,\frac{v}{e}\left(\frac{A}{V} \times \frac{1-e}{e}\right)^2$$

$$= \frac{k}{g}\,\frac{m}{r}\,\frac{(1-e)^2}{e^3}\; v \left(\frac{A}{V}\right)^2 \qquad (6)$$

The variables are subject to direct physical measurement, except A and V for the filter bed. The factors A and V, surface area and volume respectively, are functions of grain size and shape and for a spherical

grain, $\frac{A}{V} = \frac{6}{d}$ where $A = \pi d^2$ and $V = \frac{1}{6}\pi d^3$, or $\frac{A}{V} = \frac{S}{d}$ for nonspherical grains with S representing the surface area - volume shape factor.

An irregular sand grain does not have a definite diameter nor shape factor, however if there is a consistent means of measuring one diameter, then there would be one shape factor which, when multiplied by $\frac{1}{d}$ would give the area - volume ratio of the sand grain. Martin and Bowes in England carried out studies on shape factor and Fair and Hatch (1933) suggested some values as shown in TABLE I.

TABLE I

SHAPE FACTORS FOR SAND

SHAPE OF SAND	SHAPE FACTOR	RATIO TO SPHERICAL FACTOR
SPHERICAL	6.0	1.00
ROUNDED	6.1	1.02
WORN	6.4	1.07
SHARP	7.0	1.17
ANGULAR	7.7	1.29

(Fair and Hatch, 1933)

For the unstratified filter bed based on a 100 gram bed as a whole,

$$\frac{h}{L} = \frac{k}{g}\,\frac{m}{r}\,\frac{(1-e)^2}{e^3}\,v\left(\frac{S}{100}\,\sum\left(\frac{P}{d}\right)\right)^2 \tag{7}$$

S = surface area - volume shape factor

P' = weight in grams of sand grains between two adjacent sieves

d = grain size taken as the geometric mean of two adjacent sieve sizes

The equation for head loss in a stratified bed is

$$\frac{h}{L} = \frac{k}{g}\ \frac{m}{r}\ \frac{(1 - e)^2}{e^3}\ v\ \frac{S^2}{100}\ \Sigma\left(\frac{P'}{d^2}\right) \tag{8}$$

2.5 In the Carman - Kozeny equation for computing the frictional head loss through porous beds of nonconsolidated particles, Rich (1961) sets out the procedure for developing this equation. The Darcy - Weisbach relationship for energy loss in a liquid flowing through a pipe is:

$$h = f\ \frac{L}{d}\ \frac{v^2}{2g} \tag{9}$$

This equation is dimensionally homogenous and applies for any consistent system of units. The friction factor f is dimensionless. As the channel cross-sections in the filter are geometrically irregular and indeterminate the diameter term d is replaced by an equivalent term $4H_r$ where H_r is the hydraulic radius equal to the channel volume divided by the wetted surface area.

$$H_r = \frac{e}{(1 - e)}\ \frac{V}{A} \tag{5}$$

$\bar{v} = \frac{v}{e}$ where $\bar{v}$ = mean velocity of flow through the filter bed channels (10)

$\frac{V}{A} = \frac{\Theta d}{6}$ where Θ = dimensionless grain shape factor (11)

From the equation $h = \frac{f}{4} \frac{L}{H_r} \frac{\bar{v}^2}{2g}$ and the three relationships above,

the Carman – Kozeny equation is obtained for uniform size grains:

$$h = f' \frac{L}{\theta d} \frac{(1-e)}{e^3} \frac{v^2}{g} \quad (12)$$

$$f' = 150 \frac{(1-e)}{R} + 1.75 \text{ wherein } R = \text{Reynolds number} \quad (13)$$

$$R = v\theta d \frac{r}{m} = \frac{v\theta d}{n} \quad (14)$$

FIGURE 1 is a correlation curve from experimental data for friction factor f' and Reynolds number R

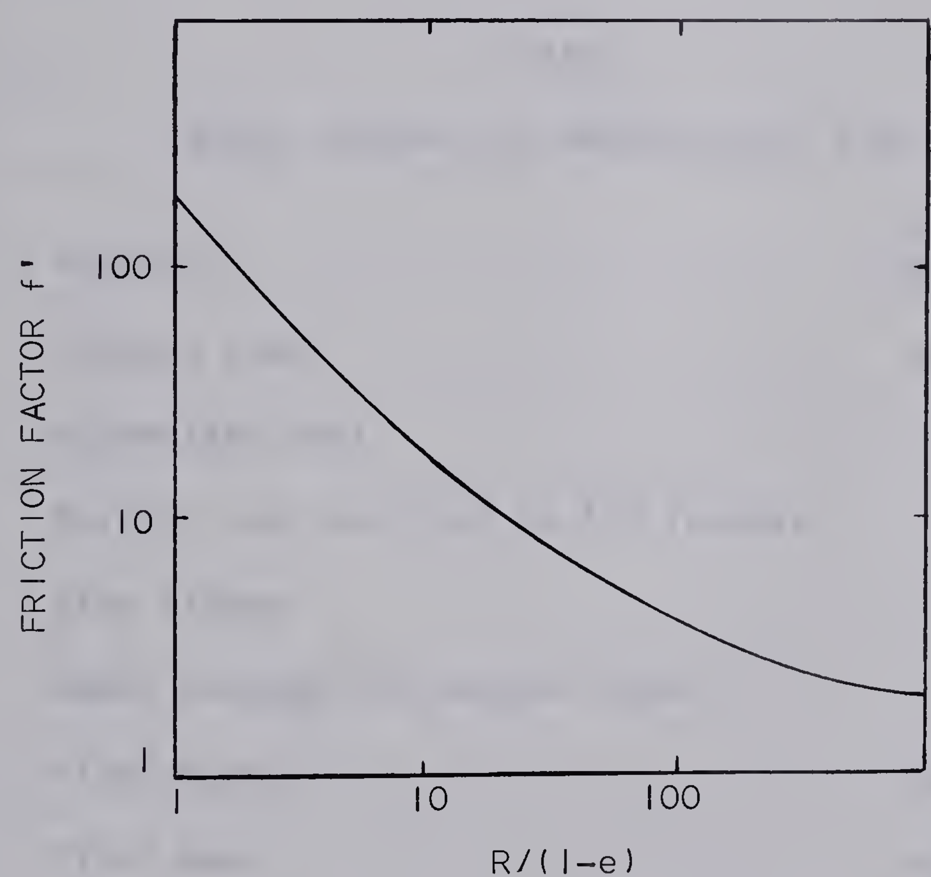


FIGURE 1 FRICTION FACTOR FOR BEDS OF SOLIDS (Foust, 1960)

For filter beds of mixed – size grains

$$d = \frac{6}{\theta} \frac{V}{A} \text{ and } \frac{A}{V} \text{ for the bed } = \frac{6}{\theta} \sum \left(\frac{P}{d}\right) \quad (15)$$

$$h = f' \frac{L}{6} \frac{A}{V} \frac{(1-e)}{e^3} \frac{v^2}{g} \quad (16)$$

P represents the fraction by weight of grains retained between adjacent sieves in a sieve analysis of the media and d is the geometric mean size of the two adjacent sieve openings. Leva (1951) derived an equation for determining most geometric shapes

$$\theta = 4.90 \left(\frac{V'}{A'}\right)^{2/3} \tag{17}$$

where V' = volume of a single grain in cubic feet

and A' = surface area of a single grain in square feet

TABLE II is a tabulation of shape factors of materials having non-spherical grains.

TABLE II

SHAPE FACTORS FOR NONSPHERICAL PARTICLES

MATERIAL	NATURE OF GRAIN	θ
Crushed glass	jagged	0.65
Pulverized coal		0.73
Natural coal dust (up to 3/8 inches)		0.65
Mica flakes		0.28
Sand, average for various types		0.75
Flint sand	jagged	0.66
Flint sand	jagged flakes	0.43
Ottawa sand	nearly spherical	0.95
Wilcox sand	jagged	0.63
Sand	rounded	0.82
Sand	angular	0.73

(Carmon, 1937)

2.6 Fair and Geyer (1954), use the dimensional analysis approach by Rose (1945, 1949) for their text, wherein

$$\frac{h}{L} \text{ is a function of } \left(\frac{vd}{n}\right) \left(\frac{v^2}{gd}\right) (e)$$

The kinematic viscosity $n = \frac{m}{r}$

By equating the drag force exerted on a particle settling in a fluid

$$\left[(v_s^2 \, d^2 \, r) \times \text{function of } \left(\frac{v_s d}{n}\right), \text{ where } v_s = \text{settling velocity}\right]$$

and the head loss between two horizontal planes through a sand bed one grain diameter apart and one grain diameter square in area, with the porosity e included to account for packing of sand grains, the above relationship is obtained. Experimental investigations of filter beds of smooth, closely graded, spherical grains indicate that $\frac{h}{L}$ varies as $\left(\frac{v^2}{gd}\right)$ and $\left(\frac{1}{e}\right)^4$. Balancing the equation by a resistance coefficient 1.067 C_d, where C_d is the coefficient of drag and is a function of Reynolds number, the equation is obtained for resistance to flow by beds of granular material.

$$\frac{h}{L} = 1.067 \, \frac{C_d}{g} \, \frac{1}{e^4} \, \frac{v^2}{d} = 0.178 \, \frac{C_d}{g} \, \frac{v^2}{e^4} \, \frac{A}{V} \tag{18}$$

For spheres the observational relationship between C_d and R is approximated by

$$C_d = \frac{24}{R} + \frac{3}{R^{0.5}} + 0.34 \tag{19}$$

To account for nonspherical grains, let a equal the surface area shape factor such that $a\,d^2$ is the surface area A of a grain with diameter d, and b equal the volume shape factor such that $b\,d^3$ is

the volume V of the grain. Then $\frac{A}{V} = \frac{a}{b}\frac{1}{d}$ (20)

Table III gives approximate values of sand shape factors.

TABLE III

APPROXIMATE VALUES OF SAND SHAPE FACTORS

TYPE OF SAND	b	a/b
Angular	0.64	6.9
Sharp	0.77	6.2
Worn	0.86	5.7
Rounded	0.91	5.5
Spherical	0.52	6.0

(Fair and Geyer, 1954)

In unstratified filter beds of varying grain size but equally shaped grains, the integral equation for $\frac{A}{V}$ is reduced to: $\frac{A}{V} = \left(\frac{a}{b}\right) \sum\left(\frac{P}{d}\right)$ (21)

If stratification occurs then $\frac{h}{L}$ must be computed for each layer and totalled to obtain the overall head loss for the filter bed. With uniform porosity and modifying the integral equations to summations then:

$$\text{Total } \frac{h}{L} = 0.178 \frac{v^2}{g} \frac{1}{e^4} \frac{a}{b} \left(\sum C_d \frac{P}{d}\right) \quad (22)$$

2.7 Thus far, the derived equations for the hydraulics of filtration apply to initial head loss - that is, the flow of clear water through a filter bed of clean granular media. The mechanics of suspended-

solids removal in the same media is very complex. Two theories related to the mechanism of filtration are the interstitial-straining theory and the gravitational sedimentation theory (Feben, 1960). Other theories include adsorption due to electric charge; adhesion due to Brownian movement and convergence of streamlines between sand grains; coagulation within filter bed; biological agencies; and colloidal mesh structure on filter media. Ling (1962) states that no single one of these theories can completely explain the complex filtration phenomenon and the wide variations of applied water and the different characteristics of the filtering materials used could make any one of these theories more predominant in certain cases. Many individual investigators have carried out research to formulate and predict filter performance and their results are applicable within the limits that each investigator worked. An important contribution was the study of sand filtration with radioactive tracers by Stanley (1955). At the present time the American Water Works Association has created a Task Group to review and make recommendations concerning methods for the determination of water filtrability (A.W.W.A. Directory, 1965).

2.8 The rapid filter, predominant in use today, differs from the original slow sand filter in that the filter media can be washed and cleaned in place. The filter washing process removes the accumulated suspended matter from the filter media which was deposited during the filtering portion of the cycle. The washing of the media in a typical filter bed involves expansion of the media by an increased rate of flow upward through the bed using clear water. A scrubbing action between the

grains and shearing action between the water and the grains loosens the accumulated suspended matter which is then carried away to waste by the flow of water through the increased pore volume of the expanded bed. The hydraulics of filter washing has pertained to determination of the head loss through the expanded bed and the degree of expansion for a given velocity. The expansion of the filter media is a measure of the total combined effect of all the variables involved such as wash velocity, temperature and viscosity of the water, size, shape, grading and specific gravity of the filtering material. Expansion expressed in terms of percentage by depth can be considered a true index of the intensity of the wash and of the work done by the wash water.

2.9 An early investigation by Hulbert and Herring (1929) brought forth data to show the relationship between the variables in the hydraulics of washing rapid sand filters and the resultant expansion. The derived empirical formula from this data stated:

$$v = \left[1.04 + 0.01\,(T - 32)\right]\,(d - 0.17)\,E + \frac{5.9}{1 - (d - 0.17)} + 0.24d\,(T - 32) - 7.4 \qquad (23)$$

v = velocity of wash water in inches per minute

E = resultant expansion, expressed as percent of original depth

T = temperature of water in degrees Fahrenheit

d = diameter of grain such that 30 percent of the sample, by weight, is finer

w = unit increase in velocity divided by corresponding increase of expansion $= \frac{\Delta V}{\Delta E}$

c = intercept of expansion characteristic on axis of velocity

They found a straight-line relationship between percent expansion and the velocity of wash wherein $v = c + w\,E$. Thus c was interpreted as the velocity necessary to start expansion of the media and w as the additional rate necessary for each one percent of expansion thereafter. Other conclusions were:

1. Expansion was proportional to original thickness of sand media.
2. Expansion is independent of freeboard.
3. Expansion varies directly as the velocity of wash; inversely as the temperature of water and size of sand grains.

2.10 Fair and Hatch (1933), on the basis that the movement of sand in an expanded filter bed does not change the basic hydraulics of filtration through a stratified bed of sand, formulated an equation for the expansion of a filter bed in terms of filtration. The void ratio of the expanded bed is not constant and this was provided for in the formula. When grains of filter media are suspended in upward flowing water the drag force equals the effective weight of the grains in water, or by formula:

$$h\,r\,g = L'\,(r_s - r)\,g\,(1 - e')$$

$$\frac{h}{L'} = \frac{(r_s - r)\,(1 - e')}{r} \qquad (24)$$

Substituting in the equation (6) for head loss in filtration (reference paragraph 2.4) results in the following equation:

$$\frac{(e')^3}{1 - e'} = \frac{k}{g} \frac{m}{r_s - r} v \left(\frac{S}{d}\right)^2 \tag{25}$$

Again assuming the porosity ratio is uniform throughout individual sand layers then

$$L' = L \frac{(1 - e)}{(1 - e')} \tag{26}$$

The depths of the individual expanded layers are added together to find the total depth of the expanded bed

$$L'_t = \sum \left(\frac{L(1 - e)}{1 - e'}\right) \tag{27}$$

The depth of the unexpanded layers is proportional to its weight of sand, P. Fair and Hatch used a total weight of 100 grams of sand thus

$$\frac{L}{L_t} = \frac{P'}{100} \tag{28}$$

$$L'_t = \frac{1 - e}{100} \sum \left(\frac{P'}{1 - e'}\right) L_t \tag{29}$$

where L'_t = total depth of the expanded bed.

2.11 With reference to FIGURE 2 from Rich (1961), the pressure drop due to the frictional resistance of the filter media, and its porosity is related to the velocity of the wash water. At very low but increasing velocities the grains remain undisturbed (fixed bed) however the pressure drop increases rapidly. At the point of critical velocity, v_c, the pressure drop is approximately equal to the effective weight of the grains, and the effective weight is the maximum frictional resistance offered by the grains free to move in the upward flow of water. When the approach velocity reaches critical point the effective weight of the grains is just balanced by the drag force. Thereafter the grains are lifted more and more, increasing the porosity and expanding the bed. At the point of

grain transport the velocity v'_c is about equal to the terminal velocity of the grains. Thus there is almost full pressure drop but no expansion as the velocity increases to v_c. Between point of velocity v_c and v'_c the filter media expands with only a slight increase in pressure drop. With a velocity of v'_c the grains are transported by the water.

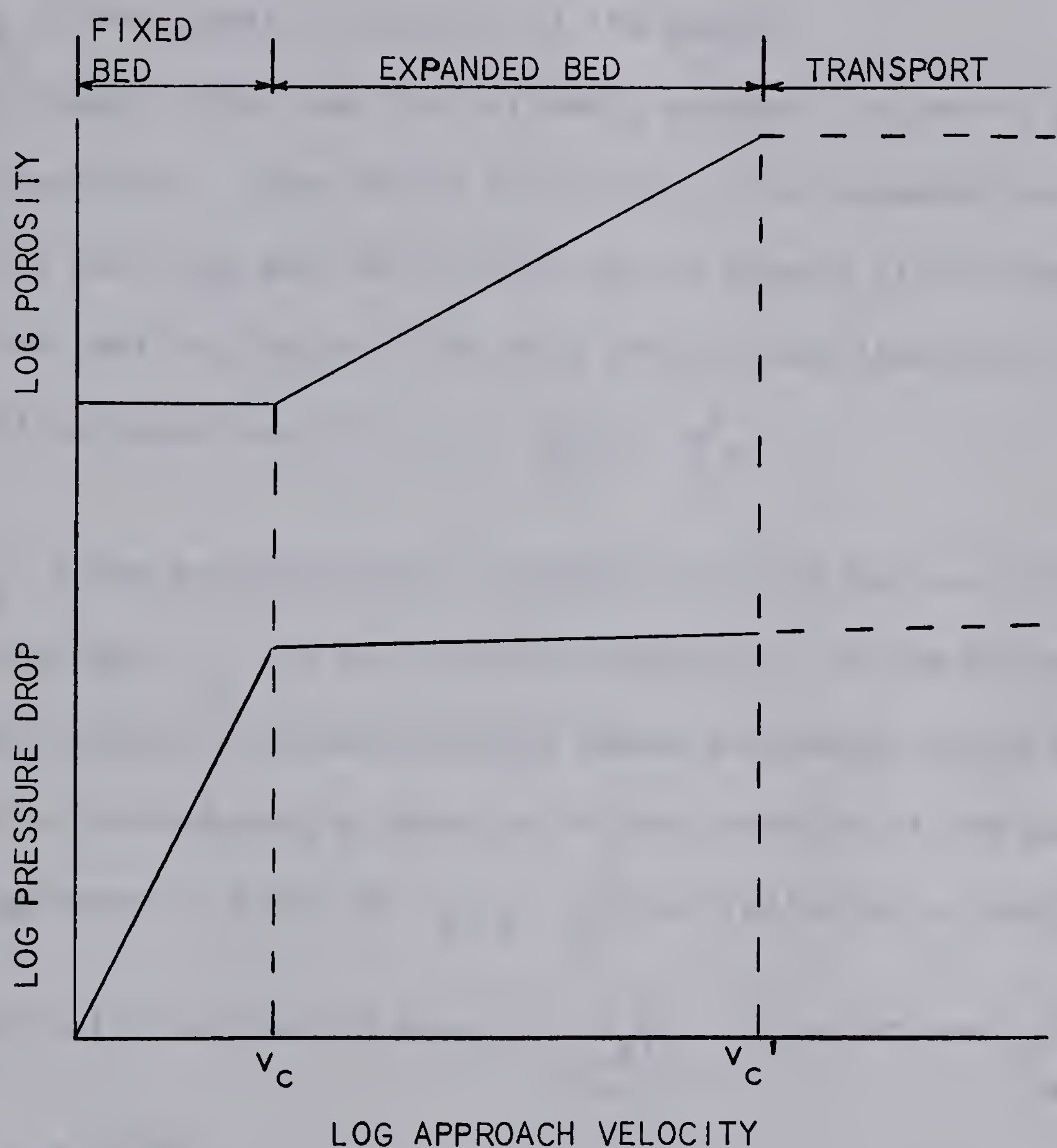


FIGURE: 2 POROSITY AND FRICTIONAL PRESSURE DROP VS APPROACH VELOCITY UPWARD FLOW THROUGH AN UNCONSOLIDATED, POROUS MEDIA OF UNIFORMLY SIZED PARTICLES (Rich, 1961).

2.12 The equation for head loss in expanding the filter media from paragraph 2.10

$$\frac{h}{L'} = \frac{r_s - r}{r} (1 - e') \quad \text{may be modified to} \tag{24}$$

$$\frac{h}{L'} = (G_s - 1) \quad (1 - e') \tag{30}$$

where G_s is the specific gravity of the media.

Fair and Geyer (1954) use the following approach to derive an expression for bed expansion. They state the grains in an expanded bed do not settle, as the drag exerted on them by the upward flow of wash water equals the settling force. The drag force, from dimensional analysis and verified experimentally is $C_d \; A_c \; r \; \frac{v_s^2}{2}$

where A_c is the projected area of grain at right angles to the direction of settling and v_s is the settling velocity. In the filter wash v (approach velocity) is used and the above expression for drag force is modified by introducing a function of the porosity of the expanded bed, thus drag force is equal to $C_d \; A_c \; r \; \frac{v^2}{2}$ multiplied by a function of e'.

Therefore this function is equal to $\left(\frac{v_s}{v}\right)^2$. By experiment $\frac{1}{(e')^9} = \left(\frac{v_s}{v}\right)^2$

$$\text{or} \quad e' = \left(\frac{v}{v_s}\right)^{0.22}. \tag{31}$$

From paragraph 2.10, the Fair and Hatch (1933) equation for expansion for a bed of uniform sand grains

$$\frac{L'}{L} = \frac{(1 - e)}{(1 - e')} \tag{32}$$

is modified by Fair and Geyer (1954) as follows

$$\frac{L'}{L} = \frac{(1 - e)}{1 - \left(\frac{v}{v_s}\right)^{0.22}} \qquad (33)$$

Similarly for the expansion of a stratified bed, the grains of various sizes are lifted into suspension when v becomes greater than $e^{4.5}$ v_s for the specific grain sizes.

Assuming the grains between adjacent sieves in a sieve analysis are for the most part uniform in size then the integral equation for the expansion ratio, modified to summations is:

$$\frac{L'_t}{L_t} = (1 - e) \sum \frac{P}{1 - \left(\frac{v}{v_s}\right)^{0.22}} \qquad (34)$$

2.13 Thus the hydraulics of filtration has been formulated generally with respect to sand media with a surface area-volume shape factor to account for grain shapes that deviate from a sphere. FIGURE 3 is a composite photograph of the typical shapes of filter sands. It will be shown how the shape of coke grains differ from the sand grains and that there is a considerably higher porosity in coke filter media as compared to sand or anthracite. The theory of filtration will be compared with the experimental data obtained from the coke filter media.

FIGURE 3: SHAPE OF FILTER SANDS
(Fair and Hatch, 1933)

1.	ANGULAR SAND	SHAPE FACTOR	7.7
2.	SHARP		7.4
3.	WORN		6.4
4.	ROUNDED		6.1

SHAPE FACTOR OF SPHERICAL SAND 6.0

CHAPTER III

EXPERIMENTAL INVESTIGATION

3.1 Model filters were constructed for the investigation of three filter media - coke, composite coke and sand. The filter influent of constant turbidity was prepared and mixed in overhead tanks and gravity fed at constant head to the model filter. Head loss at various intervals of depth of filter media and the filter effluent turbidity were recorded hourly over the length of the filter runs. Five rates of flow were investigated, 2.4, 5.0, 8.5, 12.0 and 15.0 U.S.gpm/sq.ft. Seven preliminary filter runs were made to determine the most applicable test conditions followed by fifteen filter runs. Filter washing tests were made for each filter media. The experimental data was plotted and evaluated.

3.2 Coke is the residue obtained when coking coal is subjected to destructive distillation. Consisting mainly of carbon, it is porous, hard and has a sub-metallic lustre in the dry state. Dr. N. Berkowitz (1960) states that coking coals are specialized members of the coal series and by definition are coals that will, when heated to sufficiently high temperatures, pass through a transient plastic state in which, in the ideal case, they will successively soften, swell and resolidify into a coherent cellular coke. The coke samples were supplied by the Research Council of Alberta to the required specifications. Michel coke in lump form from the coke ovens in Michel, British Columbia, and made from

coking coals in that area was crushed, sieved and graded to the same grain size and grading as the sand media in the control sand filter. TABLE IV presents this grain size and grading and from FIGURE 4 the straight line plot of the same data on a logarithm probability scale can be observed.

TABLE IV

GRAIN SIZE AND GRADING FOR MICHEL COKE AND CONTROL SAND FILTER MEDIA

U.S. Sieve Number Passing	Retained	Percent Passing	Percent Retained
14	16	100	4
16	20	96	26
20	30	70	44
30	40	26	22
40	50	4	4
50	-	0	0

In the process of making coke, additives can be used to obtain coke of varying specific gravities. The composite coke media consisted of nickel coke of specific gravity 2.87, sand coke 2.16, and Michel coke with no additive 1.83 (ASTM D854-58, Specific Gravity of Soils). Several trials were made to determine suitable additives in the proper proportion and thus obtain the required specific gravity in the finished coke sample without it undergoing change when subjected to the flowing water in the filter tube. To design the grain size and specific gravity of the composite media and obtain reverse stratification in the filter, theoretical calculations of settling velocity and grain diameter for several specific gravities were made.

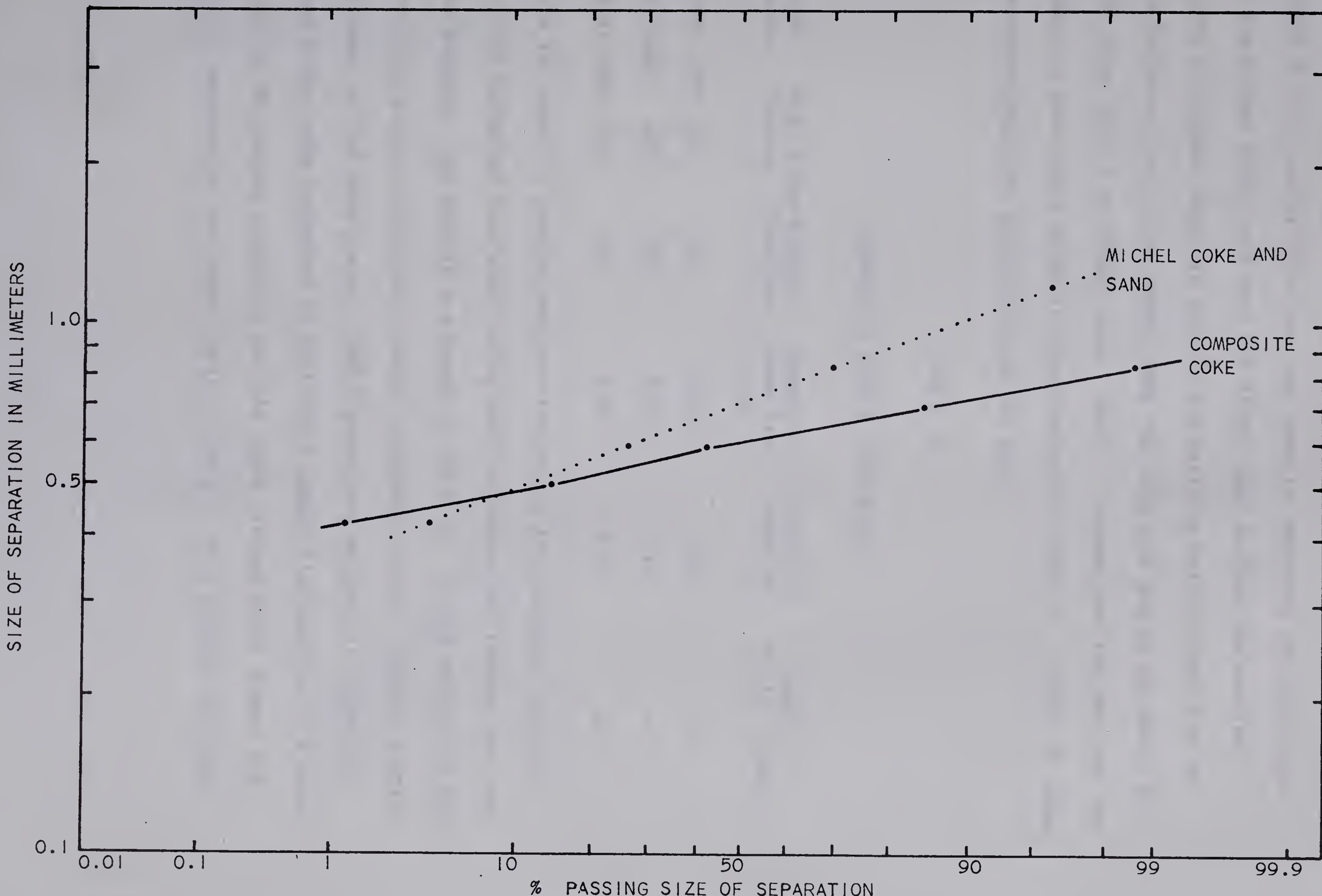


FIGURE 4: GRAIN SIZE AND GRADING THREE FILTER MEDIA

FIGURE 5, the plot of this data, was used to determine the grain size of the nickel coke, sand coke and Michel coke so that the smallest grains of highest specific gravity and settling velocity would be on the bottom of the filter media, next the sand coke and on top would be the larger grains of Michel coke. TABLE V summarizes the data for the composite coke media which is also plotted on FIGURE 4. FIGURE 6 shows microphotographs of grains of coke and sand.

TABLE V

COMPOSITE COKE FILTER MEDIA

Coke Sample	U.S. Sieve Number Passing	U.S. Sieve Number Retained	Geometric Mean Size mm	Specific Gravity	Depth in Filter Inches
Michel Coke	20	30	0.70	1.83	5
Sand Coke	25	35	0.59	2.16	9
Nickel Coke	30	40	0.50	2.87	10

Tests for specific gravity were carried out by the technical staff of the Soil Mechanics Laboratory using heat and vacuum air removal for the coke samples. The results are noted in TABLE V. A coke durability test simulating actual conditions in water treatment did not indicate significant wear of the coke grains. 306.3 grams, dry weight, of 16/20 U.S. sieve Michel coke subjected to continuous upward flow washing in a model filter at 50 percent expansion for 744 hours yielded 295.9 grams, dry weight, retained on the number 20 U.S. sieve or 96.7 percent retained.

Figure 4. The sand of this soil [illegible] is between the grain size of the [illegible] sands, [illegible] in Table 1. [illegible] specific gravity [illegible] at the [illegible] of the [illegible]. [illegible] Figure 4 [illegible].

Table 1

[illegible]

Sand	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	20	30	0.10	1.03	3
[illegible]	40	50	0.28	[illegible]	8
[illegible]	30	40	[illegible]	[illegible]	12

Tests for specific gravity were carried out [illegible] the Soil Mechanics Laboratory, [illegible]. The results are shown in Table 1. [illegible]

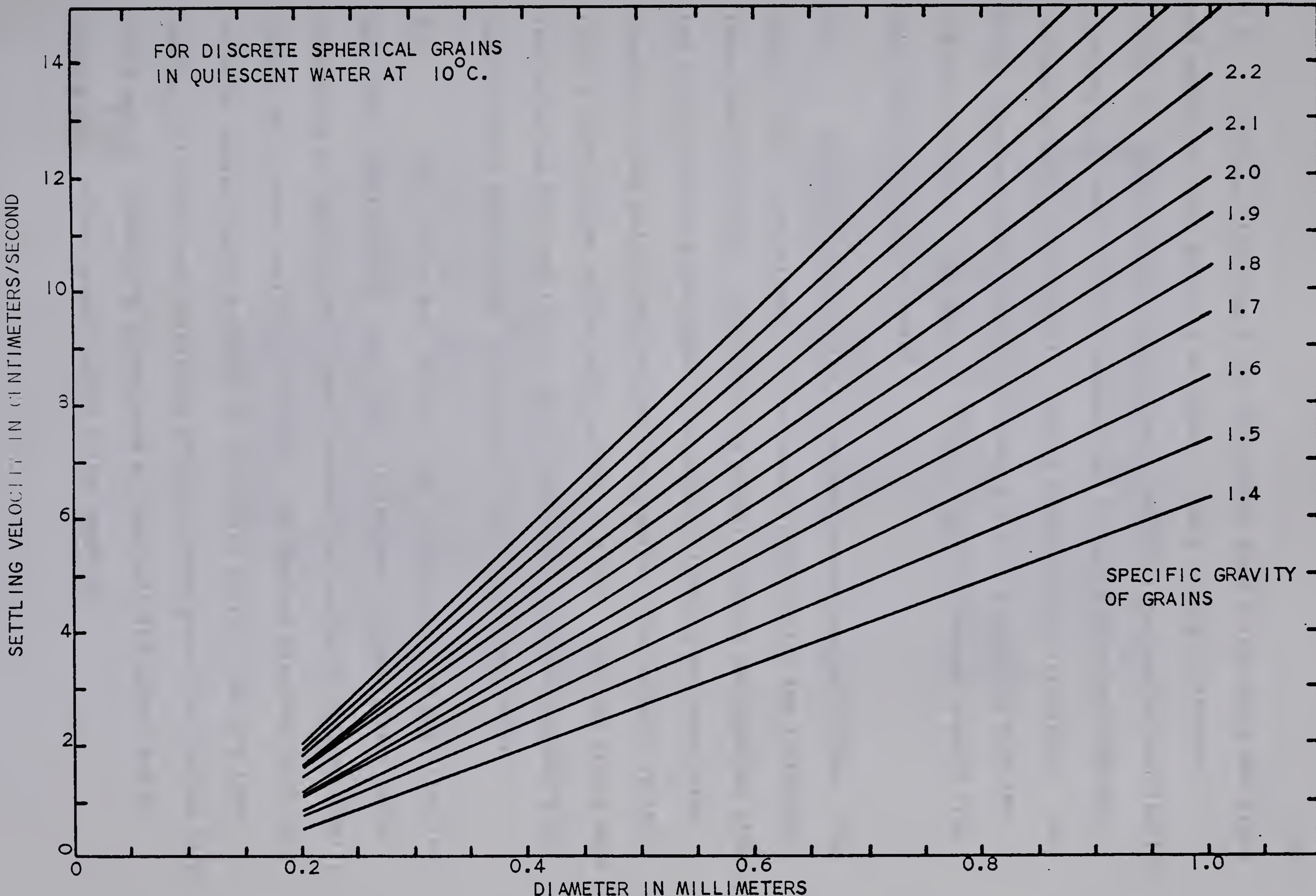
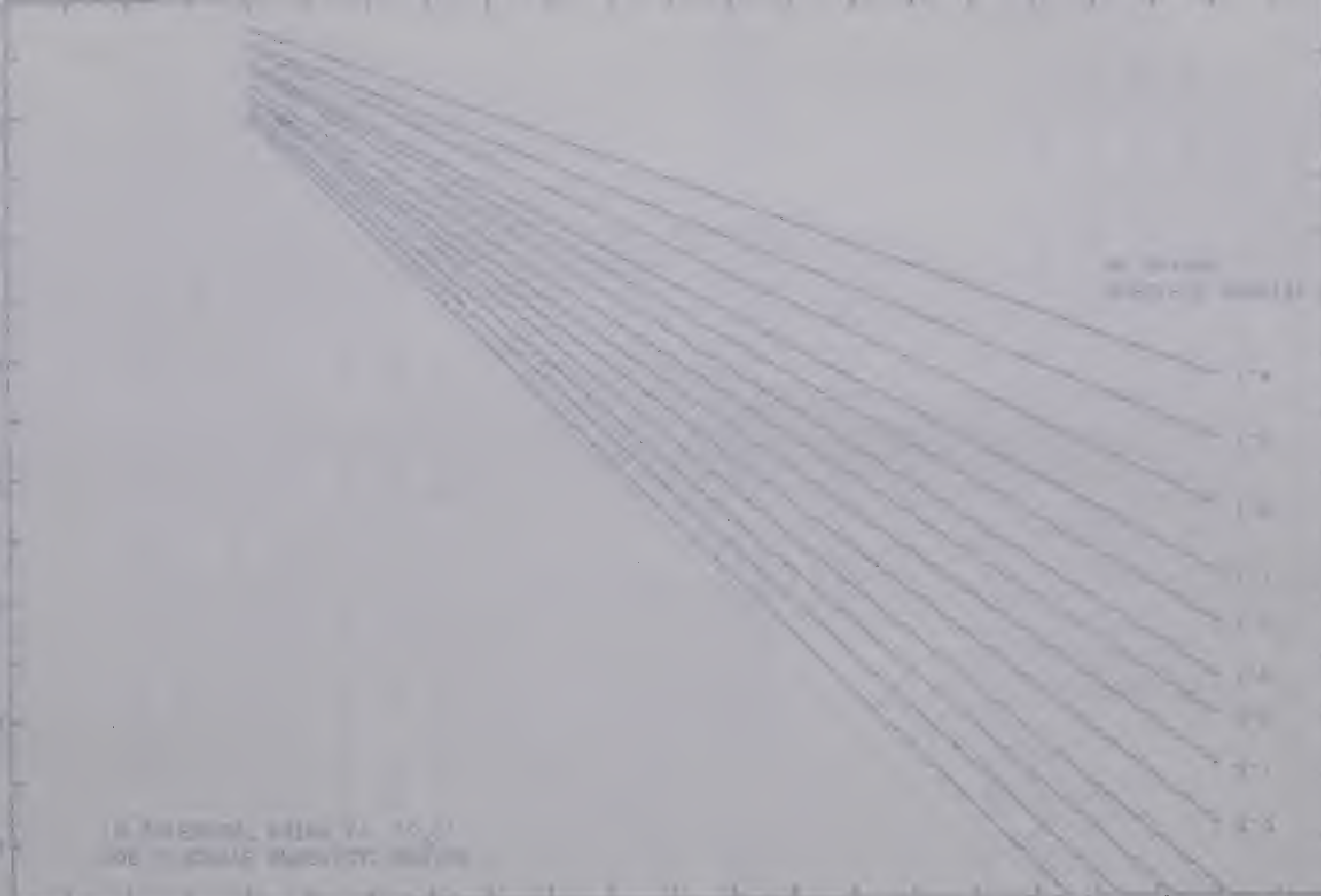


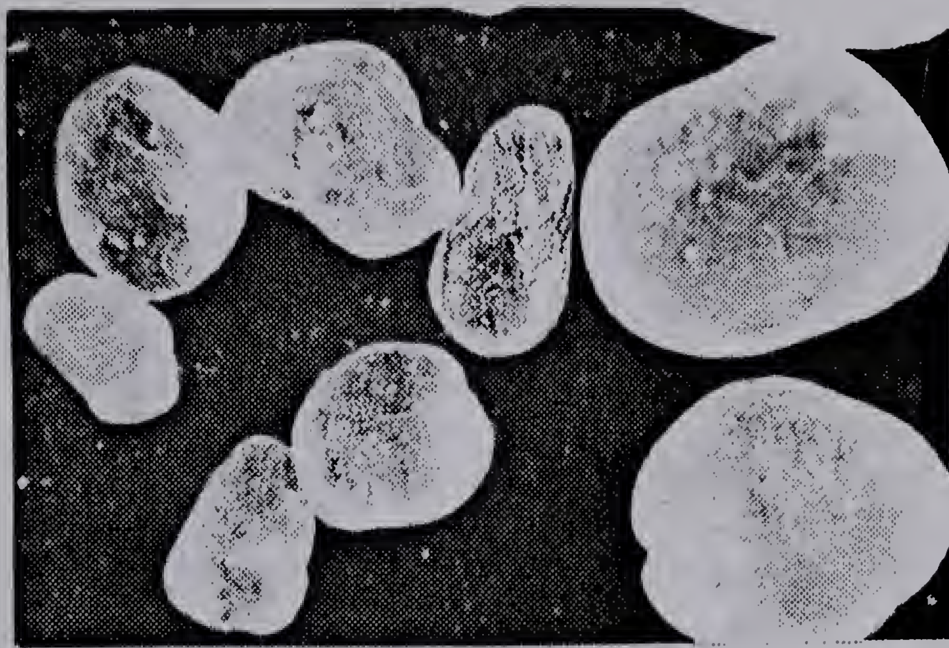
FIGURE 5: SETTLING VELOCITY VS GRAIN DIAMETER AT VARIOUS SPECIFIC GRAVITIES



3.3 Ottawa silica sand for the control sand filter media was sized and graded by sieve analysis as shown in TABLE IV and plotted on FIGURE 4. TABLE VI is a typical specification of grain size distribution by sieve size from A.W.W.A. Standard for Filtering Material (B100-53). The medium sand is suitable for average conditions of filtration. The Michel coke and control sand filter media are in accordance with the A.W.W.A. Standard. The shape of the sand grains differed greatly from coke grains as shown in FIGURE 6.

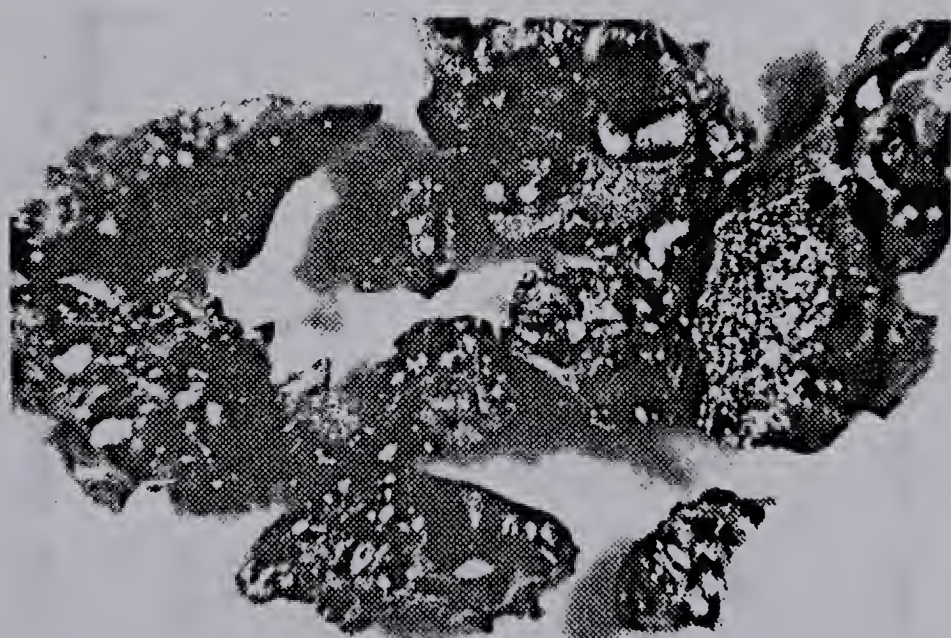
3.4 Porosity tests of the filter media were made as follows. The actual total volume of media in the model filter during the filtration tests was determined. The oven-dried weight of media was obtained after the filter runs were concluded. The volume of solids was calculated knowing the dry weight and the specific gravity. The porosity is the ratio of pore volume to the total volume of filter. For the silica sand the value was 0.40 and for the Michel coke 0.70. A common porosity of natural sands and gravels is 40 percent (Fair and Geyer, 1954).

3.5 The filter gravel supports the filter media and equalizes the wash water distribution. Each model filter had the same gravel media consisting of four - 3 inch layers graded from coarse to fine vertically upward for a total depth of 12 inches. The maximum size was 15/16 inch diameter agates placed adjacent to the filter outlet, then 5/8 inch agates, 1/4 inch river gravel and 4/8 U.S. sieve gravel for the top layer. There was no intermixing of the sand or coke with the gravel and no displacement of the gravel during filter washing.



GRAINS FROM CONTROL SAND MEDIA

14/50 U.S. SIEVE, 35X



GRAINS FROM MICHEL COKE MEDIA

14/50 U.S. SIEVE, 35X

FIGURE 6: MICROPHOTOGRAPHS GRAINS OF FILTER MEDIA

TABLE VI

GRAIN SIZE DISTRIBUTION BY SIEVE SIZE

SIEVE NUMBER		A.S.A. SIEVE OPENING MM	FINE	MEDIUM	COARSE
			EFFECTIVE SIZE MM		
TYLER NO.	U.S. NO.		0.35 – 0.45	0.45 – 0.55	0.55 –
			PERCENT PASSING SIEVE		
14	16	1.19	94 – 100	84 – 99	68 – 93
20	20	0.84	71 – 97	49 – 84	30 – 71
28	30	0.59	31 – 73	14 – 39	6 – 31
35	40	0.42	6 – 25	2 – 6	0 – 1
48	50	0.30	0 – 3	0 – 1	0

AWWA, B100–53

3.6 In the application of turbidity to the filter influent, the formation of reproducible dispersions was most important. Kaolin in city tap water was selected for the filter influent. In all the filtration tests kaolin, K-5 acid-washed and of the same Lot number from Fisher Scientific Company was used. Turbidity remaining in the filter effluent was a measure of the efficiency of the filter for removing suspended solids. Kaolin is essentially a clay material low in iron, insoluble and easily dispersed in water, nearly white in color, a hydrous aluminum silicate and characterized by the mineral kaolinite. Kaolin clays are used in the laboratory for turbidity suspensions in water treatment research (Black and Hannah, 1965).

TABLE VII

PRELIMINARY TURBIDITY TESTS[1]

MATERIAL[2]	HEAD LOSS[3] FEET	TIME[4] HOURS	TURBIDITY[5] INFLUENT[2]	TURBIDITY[5] EFFLUENT
Bentonite	6.0	9	73.5	99.0
Fuller's Earth	6.4	$2\frac{1}{2}$	85.5	99.0
Kaolin	2.5	18	56.5	99.0

1. 2.4 U.S.gpm/sq.ft. Rate of flow
2. 60 ppm in City Tap Water
3. 24-inch Depth, Control Sand Filter Media
4. From start of Filtration Test
5. Spectrophotometer - Percent Light Transmission

Fuller's earth and bentonite were investigated in the preliminary tests along with kaolin. TABLE VII summarizes the characteristics of the turbidity materials. The low spectrophotometer reading for 60 ppm kaolin allows a greater and more favorable range on the instrument scale. The bentonite and Fuller's earth did not penetrate the depth of the filter media as well as kaolin and a high head loss resulted in about 9 and 2½ hours respectively. The white kaolin deposits were easily observed in the filter media and there was no difficulty in maintaining a constant influent turbidity.

3.8 Standard Methods (1960) states, "turbidity is an expression of the optical property of a sample which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample and attempts to correlate turbidity with the weight concentration of suspended matter are impractical as the size, shape and refractive index of the particulate matter are of most importance optically but bear little direct relationship to the concentration and specific gravity of the suspended matter."

3.9 Three types of instruments were initially used for turbidity measurement. The Hellige turbidimeter utilizing the Tyndall effect principle, compares a beam of light passing upward through the turbid sample to the light which is scattered upward by the suspended particles when they are illuminated from the side. Calibration curves were made up for kaolin clay in 4 ranges, 0 - 4 ppm, 0 - 15 ppm, 0 - 50 ppm and 0 - 150 ppm, by using 2 filters and 2 viewing depths. When the two fields mentioned above are compared it is often difficult to judge the

point of uniform intensity and be consistent in repeated checks on the same sample. The Hach surface-scatter turbidimeter is a continuous flow nephelometer wherein a light beam illuminates the surface of a liquid sample and light that is reflected by turbidity at or near the water surface is measured. Seven standard ranges 0 - 5, 0 - 25, 0 - 100, 0 - 250, 0 - 500, 0 - 1000 and 0 - 2500 permits adjustment of the sensitivity over a wide range. However, the scale readings with a constant turbidity were different for a change in flow rate and similarly for a change from one standard range to the next higher or lower range. Technical problems in the electronic components developed and there was not sufficient time for the required maintenance. The Bausch and Lomb Spectronic 20 Spectrophotometer was used throughout the investigation for turbidity analysis. Charlot (1964) stated "colorimeters and spectrophotometers may be used for turbidimetry without any modification." With this instrument the concentration of turbidity in the sample is related to the proportion of light that is transmitted through the sample. In preliminary tests with kaolin clay turbidity, the best wave length (i.e. that which produces the largest spread of readings between a standard and a blank) was 395 millimicrons. A calibration curve FIGURE 7 for kaolin clay was made by making up the individual ppm concentrations in the 45-gallon tanks then mixing and circulating through a sump. The dilution technique was not used. The concentration vs logarithm percent light transmission in FIGURE 7 plots as a straight line indicating close conformity to Beer's law. The spectrophotometer readings were always consistent and this type of instrument was the most suitable of the types available for this specific investigation.

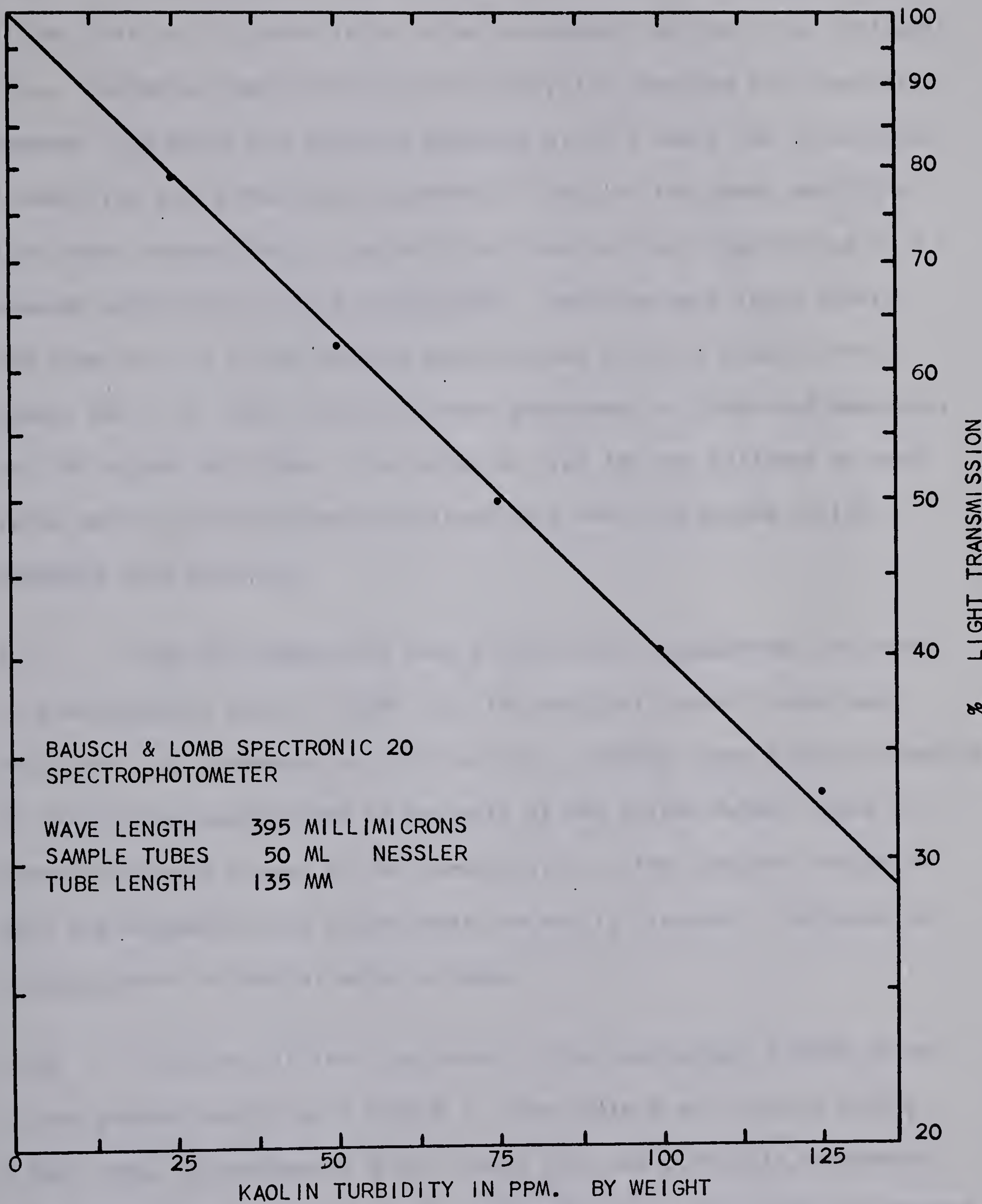


FIGURE 7: SPECTROPHOTOMETER CALIBRATION

3.10 The filtration flow rate was held constant throughout each filter test by a float-orifice valve arrangement in the filter effluent line. Rotameters were installed initially for checking the flow rates, however they would not maintain accuracy after a short run of service. A one-liter and a two-liter volumetric flask for the lower and higher flow rates respectively along with an electric timer registering to 0.1 seconds were used for flow measurement. Readings were taken hourly. The flow rate in filter washing was obtained with the same electric timer, but a 16 liter lucite cylinder graduated in liters was necessary for the higher wash rate. The rates of flow for any effluent or wash valve setting was obtained by collecting a definite volume in the measured time interval.

3.11 Open end manometers used for head loss measurement are shown in photographs 1 and 2, FIGURE 10. The vertical lucite tubing was 7/16 inch I.D. connected to 1/4 inch I.D. flexible Tygon tubing extending to the orifice connections at the wall of the filter tube. Glass T - connections were placed at the lowest point of the flexible tubing so that the manometers and tubing could be easily flushed. The manometer readings were in feet of water column.

3.12 The model filters are shown in the photographs FIGURE 10 and in the dimensioned drawing FIGURE 8. The filters were lucite tubing 9 feet long, approximately 2-3/4 inches I.D. and 0.04 sq.ft. cross-sectional area. The brass orifices on the left side of the filter, numbered 1 to 10L inclusive, were 1/4 inch I.D. and extended to the inner face of filter tube. T - connections were located adjacent to the orifices to

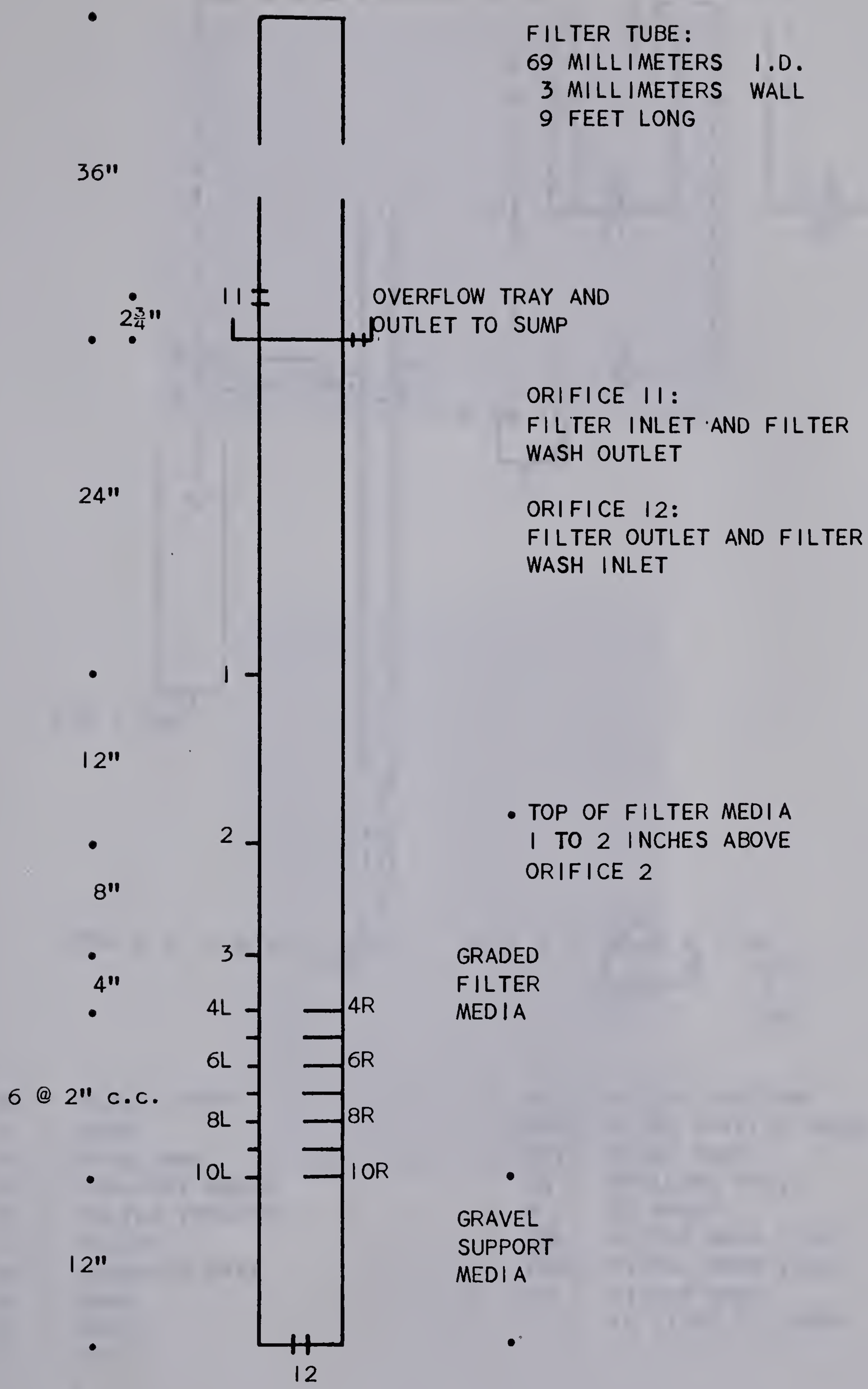
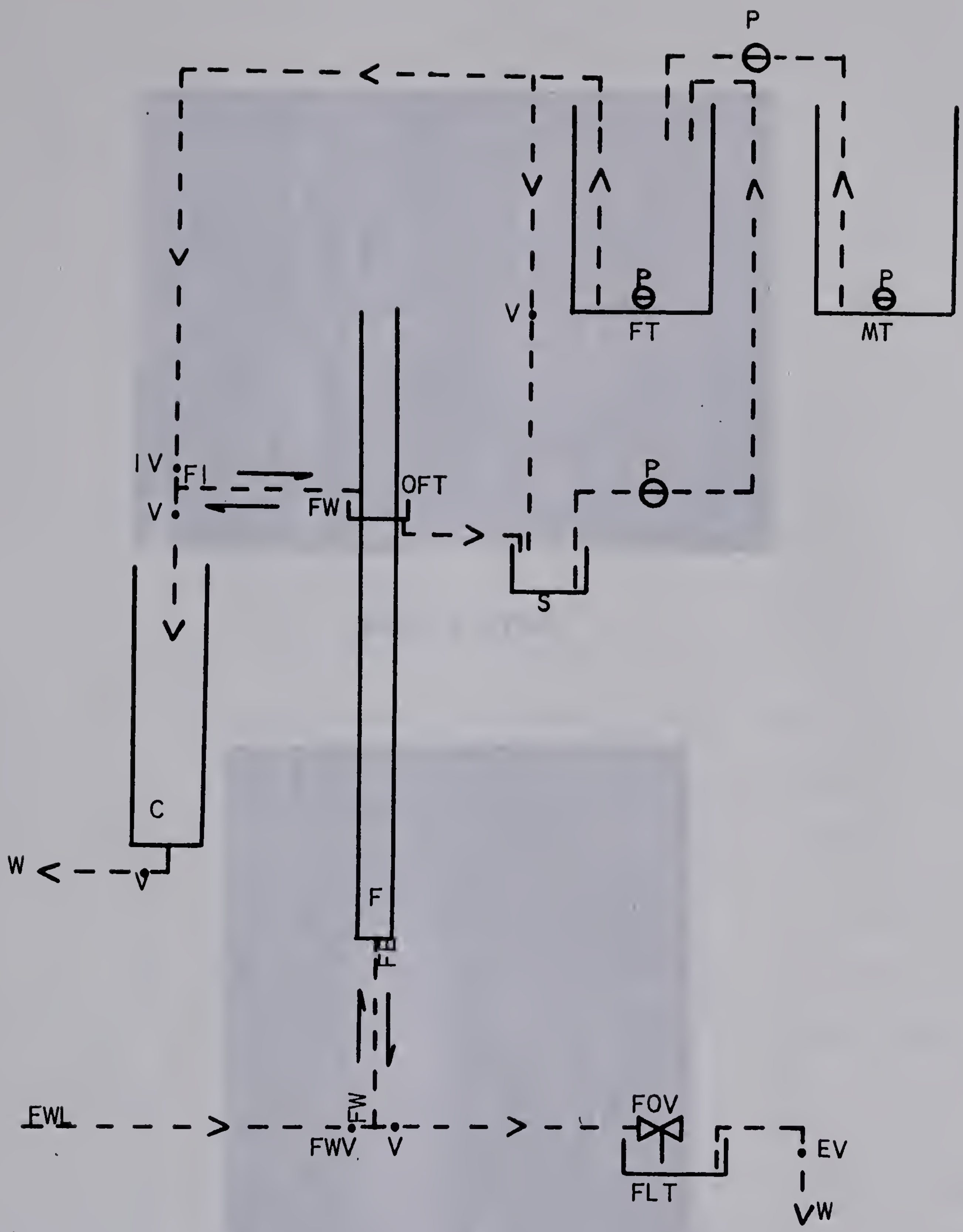


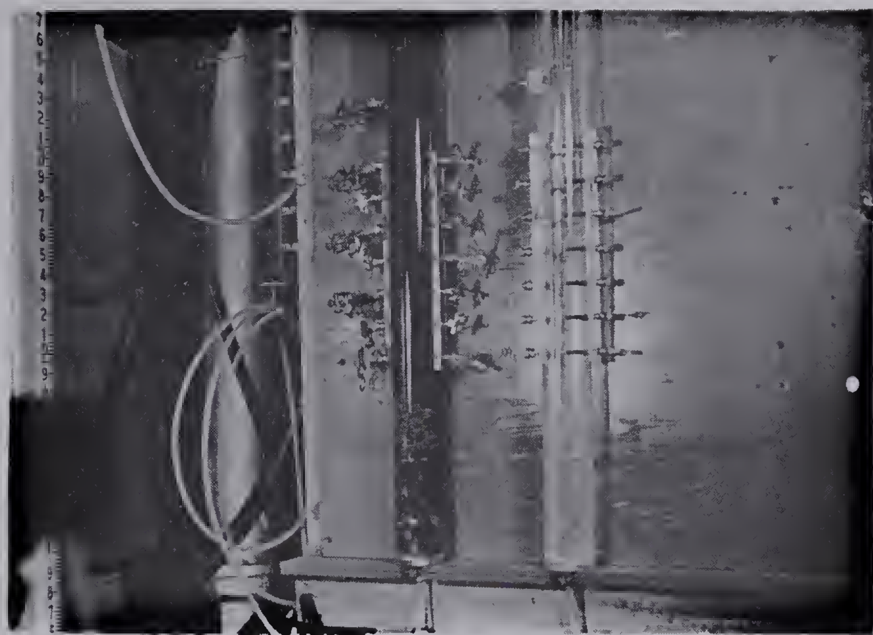
FIGURE 8: MODEL FILTER

NOT TO SCALE



MT :	MIXING TANK	FE :	FILTER EFFLUENT
P :	PUMP	FOV:	FLOAT ORIFICE VALVE
FT :	FEED TANK	FLT:	FLOAT TANK
IV :	INFLUENT VALVE	EV :	EFFLUENT VALVE
FI :	FILTER INFLUENT	W :	TO WASTE
F :	FILTER	FWL:	FILTER WASH LINE
OFT:	OVERFLOW TRAY	FWV:	FILTER WASH VALVE
S :	SUMP	FW :	FILTER WASH
V :	VALVE	C :	16 LITRE CYLINDER

FIGURE 9: FILTRATION FLOW DIAGRAM



MODEL FILTERS

FILTERS, MANOMETERS,
SUMP, MIXING TANK,
PUMP AND MOTOR,
FEED TANK

FIGURE 10: EXPERIMENTAL APPARATUS AND EQUIPMENT

allow one leg to be connected to the manometer tubing and one leg clamped for intermittent sampling. Orifice numbers 4R to 10R inclusive were 1/8 inch I.D. projecting to the centre of the filter for sampling. The smaller diameter was used to lessen the effect of the reduced cross-sectional area of filter in the horizontal plane of the orifice. 60 mesh stainless steel screens in the orifices prevented the filter media from entering the tubing. Preliminary filter tests were also made with the sand control filter using 12, 16, 24 and 28 inch depth of filter media with 3, 6 and 7 feet of water column or pressure head above the filter media to determine a suitable depth and head for this specific investigation. The 24 inch depth and 6 foot head were selected. The float-orifice valve arrangement was modified twice to obtain the capacity sufficient for the range of flows from 2.4 to 15.0 U.S.gpm/sq.ft. with the above conditions of depth and head. The model filter may be considered the same in vertical cross-section as the typical prototype. Tso-Ti Ling (1955) states "all previous investigators agreed that the results obtained from the glass-tube filter were reliable when compared with those from the large filter units."

3.13 The turbidity readings taken at intervals of time and of depth of the filter were too irregular to be considered reliable. The spectrophotometer takes a 50 milliliter Nessler sampling tube. If the filtration flow rate is 5.0 U.S.gpm/sq.ft., it would require 7.8 minutes for a 50 milliliter sample to pass through the 1/4 inch I.D. orifice and 31 minutes through the 1/8 inch I.D. orifice so that the velocity of flow entering the orifice would not exceed the velocity downward through the filter media. The volume of the orifice and tubing up to the

discharge clamp should be run to waste prior to each sampling. The tubing clamps were not suitable for the fine adjustment of flow required. Therefore this secondary investigation proved to be of such complexity to obtain reliable results that special equipment and techniques were considered necessary but were not available at the time.

3.14 Other equipment consisted of two 45 Imperial gallon plastic barrels, 34 inches in depth used for mix and feed tanks. The sump receiving the filter overflow was of 2½ gallon volume with bottom valved outlet for ½ inch pipe connection to the main circulating pump. The two circulating pumps were ¼ horsepower each. Small submersible pumps were placed on the bottom of the mix and feed tanks to keep the turbidity in suspension. ½ inch I.D. Tygon tubing carried the filter influent from the feed tank to the filter. ¼ inch I.D. Tygon tubing was used for the filter wash line connected direct to the city water supply.

3.15 With reference to flow diagram FIGURE 9 the experimental procedure was as follows. The mixing tank was filled to 45 gallons with city tap water. 20.45 grams of kaolin clay weighed on the torsion balance was slowly added to about 1500 milliliters of city tap water with continuous stirring on a magnetic stirrer until uniform suspension was apparent. The suspension was added to the water, in the mixing tank, which was in continuous circulation. After a minimum of 20 minutes mixing, a sample was checked for turbidity on the spectrophotometer and the contents were then pumped to the feed tank where it was also in continuous circulation, thence siphoned to the filter with the

influent valve setting sufficient to maintain a slight overflow at the top of the filter and thus a constant head on the filter. A second siphon feed direct to the sump helped to maintain sufficient volume in the sump for pumping and provided more circulation in the feed tank. The filter effluent passed through the float-orifice valve into the float tank with a free water surface then siphoned through the effluent valve to waste. The effluent valve is set for the required filtration flow rate and the float-orifice valve and tank is the rate-of-flow controller to maintain a constant flow throughout the filter test while the head loss across the filter media increases. To wash the filter, the influent line to orifice II was disconnected and this orifice became the overflow point for wash water which went to the 16 liter cylinder for measuring the wash flow rate, then to waste. The wash influent entered the filter at the bottom, regulated by a ¼ inch needle valve to allow 50 percent expansion of the original depth of filter media.

3.16 Filter tests were not less than 18 hours duration with head loss, influent and effluent readings made hourly. Immediately prior to each test clear water was run through the filter, the valve setting for the new flow rate was made and checked continually until the complete flow system was in equilibrium. The orifices and tubing were flushed with clear water and the manometers were checked for uniform static head.

3.17 Filter washing after each test was carried on until the wash effluent was clear. The wash influent valve was closed gradually over 1½ minutes to maintain uniform depth and grading of the filter media.

CHAPTER IV

OBSERVED DATA AND RESULTS

4.1 TABLE VIII is a summary of the experimental filter tests for the preliminary investigation of coke as a filter media. The main characteristics and purpose of each filter test are indicated. Tests 1 to 6 inclusive and Test 8 were preliminary tests. Test 7 and Tests 9 to 22 inclusive were the filtration tests to evaluate the control sand, composite coke and Michel coke media. The end point of the filtration tests was 8 feet of head loss or a condition of the effluent turbidity approaching the influent turbidity, with a duration of each test up to 18 hours. In TABLE VIII the depth of media is given in inches. The head in feet refers to the height of water column in the filter from the top of the filter media to the top of the filter tube (point of overflow). The filter influent was city tap water with clay material added to produce a high turbidity in the water. The filter influent turbidity is the concentration (ppm by weight) of clay material added to city tap water. This concentration was maintained constant by continuous circulation in the mix and feed tanks and by return pumping from the sump to the feed tank

4.2 TABLE IX is the tabulated experimental data from test 19 and TABLE X is the processed data, both typical of the evaluation tests 18 to 22 inclusive for Michel coke, 9 to 13 inclusive for composite coke and control tests 7 and 14 to 17 inclusive for sand. The results of

these tests are combined and presented graphically in FIGURES 11 to 15 inclusive (h/L vs time in hours) and FIGURES 16 to 20 inclusive (effluent turbidity in % light transmission vs time in hours) with each graph showing the applicable characteristic of the three filter media at equal flow rate. Values of unit head loss h/L from TABLE X plotted on above graphs were computed from TABLE IX by dividing the head loss in feet at Orifice 8L by the depth in feet from the top of the filter media to Orifice 8L. A comparison can be easily observed from the graphs for the coke media and the control sand media.

4.3 With reference to tests 24 and 29 to 31 inclusive clear water without turbidity was the filter influent. Filter tests at the 5 flow rates for various filter media gave the initial head loss data which was plotted on FIGURE 21. For laminar flow through the filter media there should be a straight-line relationship between unit head loss and flow rate. The data from these tests is applicable in checking the formulas for the hydraulics of filtration. Figure 22 is a graph of head loss in feet vs depth of media in feet at constant flow rate, from the same test data.

4.4 FIGURE 23 is the graph of data obtained from the filter washing tests that followed filtration tests 13, 16 and 22 for sand, composite coke and Michel coke respectively. Again the comparison may be observed for the relationship between percent expansion of the filter media and the wash flow rate in U.S.gpm/sq.ft. upward through the media.

4.5 FIGURES 24 to 36 inclusive are graphs of unit head loss at

(Text continued on Page 94)

TABLE VIII

SUMMARY OF EXPERIMENTAL TESTS

Test	Media	Depth Inches	Head Feet	Rate U.S.gpm per sq.ft.	Influent Turbidity ppm	Duration Hours	Purpose of Test
1	Sand	24	3	2.4	60 Bentonite	9	Evaluate Turbidity
2	Sand	24	3	2.4	60 Kaolin	18	Evaluate Turbidity
3	Sand	24	3	2.4	60 Fuller's Earth	2½	Evaluate Turbidity
4	Sand	24	3	2.4	100 Kaolin	18½	Evaluate Turbidity
5	Sand	12	7	6.0	50 Kaolin	9½	Evaluate Rate, Depth, Head
6	Sand	16	7	5.0	100 Kaolin	24	Evaluate Rate, Depth, Duration
8	Composite Coke	28	6	5.0	100 Kaolin	15½	Evaluate Head, Depth, Rotameters

TABLE VIII continued

Test	Media	Depth Inches	Head Feet	Rate U.S.gpm per sq.ft.	Influent Turbidity ppm	Duration Hours	Purpose of Test
14	Sand	24	6	2.4	100 Kaolin	18	Control Test with Sand
7	Sand	24	6	5.0	100 Kaolin	18	Control Test and Wash Data
15	Sand	24	6	8.5	100 Kaolin	7	Control Test
16	Sand	24	6	12.0	100 Kaolin	6	Control Test and Wash Data
17	Sand	24	6	15.0	100 Kaolin	2	Control Test and Wash Data
13	Composite Coke	24	6	2.4	100 Kaolin	18	Coke Evaluation and Wash Data
9	Composite Coke	24	6	5.0	100 Kaolin	18	Coke Evaluation and Wash Data
10	Composite Coke	24	6	8.5	100 Kaolin	18	Coke Evaluation

TABLE VIII continued

Test	Media	Depth Inches	Head Feet	Rate U.S. gpm per sq.ft.	Influent Turbidity ppm	Duration Hours	Purpose of Test
11	Composite Coke	24	6	12.0	100 Kaolin	18	Coke Evaluation
12	Composite Coke	24	6	15.0	100 Kaolin	18	Coke Evaluation
18	Michel Coke	24	6	2.4	100 Kaolin	18	Coke Evaluation
19	Michel Coke	24	6	5.0	100 Kaolin	18	Coke Evaluation
20	Michel Coke	24	6	8.5	100 Kaolin	18	Coke Evaluation
21	Michel Coke	24	6	12.0	100 Kaolin	18	Coke Evaluation
22	Michel Coke	24	6	15.0	100 Kaolin	18	Coke Evaluation Wash Data
24	Michel Coke	24	6	2.4 to 15.0 incl.	Clear Water	–	Evaluate h/L without Turbidity

TABLE VIII continued

Test	Media	Depth Inches	Head Feet	Rate U.S. gpm per sq. ft.	Influent Turbidity ppm	Duration Hours	Purpose of Test
26	Michel Coke	24	6	8.5	100 Kaolin	18	Duplication of Test 20
27	Michel Coke	24	6	8.5	100 Kaolin	6	Duplication of Test 26
24-A	Michel Coke	24	6	8.5	Clear Water	–	Duplication of Test 24 @ 8.5
29	Composite Coke	24	6	2.4 to 15.0 incl.	Clear Water	–	Evaluate h/L without Turbidity
30	New Michel Coke	21	$6\frac{1}{4}$	2.4 to 15.0 incl.	Clear Water	–	Evaluate h/L for New Coke without Turbidity
31	Sand	24	6	2.4 to 15.0 incl.	Clear Water	–	Evaluate h/L for Sand without Turbidity
23	Michel Coke 16/20 U.S. Sieve	$14\frac{1}{2}$	Wash at 50 per-cent Expansion	–	Clear Water	744	Coke durability Test by Filter Washing

TABLE VIII continued

Test	Media	Purpose of Test
25	2 – Michel Coke 1 – Composite Coke 1 – Sand	Test for Filter Media Settling in Filter Tube with Vibration
28	2 – Michel Coke 1 – Composite Coke 1 – Sand	Secondary Test for Porosity of Filter Media in Filter Tube by Measuring Volume of Water in Pores

TABLE IX

EXPERIMENTAL DATA FROM TEST 19

Time	Head Loss – Feet Orifice Number					Turbidity Influent	Turbidity Effluent		Temp. °C.
	2	3	4L	6L	8L	%LT[1]	%LT[1]	J.T.U.[2]	
								Scale 6	
6.00 a.m.	0.065	0.255	0.335	0.400	0.450	39.5	64.5	23.0	22.5
6.30	0.065	0.260	0.340	0.400	0.450	39.5	65.5	22.0	
7.30	0.070	0.270	0.355	0.420	0.470	39.0	66.5	21.5	23.0
8.30	0.075	0.285	0.370	0.440	0.495	39.5	71.5	19.0	
9.30	0.080	0.295	0.380	0.450	0.500	40.0	72.5	18.5	
10.30	0.080	0.315	0.405	0.480	0.535	40.0	77.0	15.0	22.0
11.30	0.085	0.325	0.420	0.495	0.545	40.0	77.0	15.0	
12.30 p.m.	0.095	0.355	0.455	0.525	0.590	40.0	–	15.5	
1.30	0.100	0.365	0.470	0.545	0.600	40.0	76.5	16.0	

1. Percent light transmission – Spectrophotometer

2. Jackson Turbidity Units – Turbidimeter – Readings not reliable

TABLE IX continued

Time	Head Loss – Feet, Orifice Number					Turbidity, Influent	Turbidity, Effluent		Temp. °C.
	2	3	4L	6L	8L	%LT[1]	%LT[1]	J.T.U.[2]	
								Scale 6	
2.30	0.105	0.385	0.485	0.565	0.625	40.0	76.5	16.0	23.5
3.30	0.110	0.405	0.510	0.595	0.650	40.0	78.5	15.5	22.5
4.30	0.115	0.420	0.525	0.610	0.675	40.0	–	15.5	
5.30	0.120	0.440	0.550	0.630	0.695	39.5	79.5	15.5	24.0
6.30	0.125	0.460	0.565	0.650	0.715	39.5	79.5	15.0	23.0
7.30	0.135	0.495	0.610	0.695	0.760	40.5	82.0	15.5	
8.30	0.145	0.515	0.630	0.720	0.785	40.5	82.0	21.5	
9.30	0.160	0.540	0.660	0.750	0.815	40.0	86.5	25.0	23.5
10.30	0.170	0.565	0.690	0.785	0.850	40.0	84.5	16.5	
11.30	0.185	0.600	0.725	0.820	0.885	40.0	84.0	13.5	
12.00	0.190	0.610	0.740	0.835	0.900	40.0	82.0	13.5	

TABLE X

PROCESSED DATA FROM TEST 19

Time Hours	Unit Head Loss at Orifice 2	3	4L	6L	8L
½	*0.66	0.33	0.30	0.28	0.25
	**0.66	0.28	0.24	0.19	0.15
1	0.66	0.34	0.31	0.28	0.25
	0.66	0.29	0.24	0.18	0.15
2	0.71	0.35	0.32	0.29	0.27
	0.71	0.30	0.25	0.19	0.15
3	0.76	0.37	0.34	0.31	0.28
	0.76	0.31	0.26	0.21	0.16
4	0.81	0.39	0.35	0.31	0.28
	0.81	0.32	0.26	0.21	0.15
5	0.81	0.41	0.37	0.34	0.30
	0.81	0.35	0.27	0.22	0.16
6	0.86	0.42	0.38	0.34	0.31
	0.86	0.36	0.28	0.22	0.15
7	0.96	0.46	0.41	0.37	0.33
	0.96	0.39	0.30	0.21	0.19
8	1.01	0.48	0.43	0.38	0.34
	1.01	0.40	0.32	0.22	0.16
9	1.06	0.50	0.44	0.39	0.35
	1.06	0.42	0.30	0.24	0.18

* Unit Head Loss from top of Filter Media to Orifice

** Unit Head Loss between Orifices

TABLE X continued

Time	Unit Head Loss At Orifice				
Hours	2	3	4L	6L	8L
10	1.11	0.53	0.46	0.42	0.37
	1.11	0.44	0.32	0.25	0.17
11	1.16	0.55	0.48	0.43	0.38
	1.16	0.46	0.32	0.26	0.19
12	1.21	0.57	0.50	0.44	0.39
	1.21	0.48	0.33	0.24	0.19
13	1.26	0.60	0.51	0.45	0.40
	1.26	0.50	0.32	0.25	0.19
14	1.37	0.65	0.56	0.48	0.43
	1.37	0.54	0.34	0.26	0.19
15	1.47	0.67	0.57	0.50	0.44
	1.47	0.55	0.35	0.27	0.19
16	1.62	0.70	0.60	0.52	0.46
	1.62	0.57	0.36	0.27	0.19
17	1.72	0.74	0.63	0.55	0.48
	1.72	0.59	0.38	0.28	0.19
18	1.87	0.78	0.66	0.57	0.50
	1.87	0.62	0.38	0.28	0.19

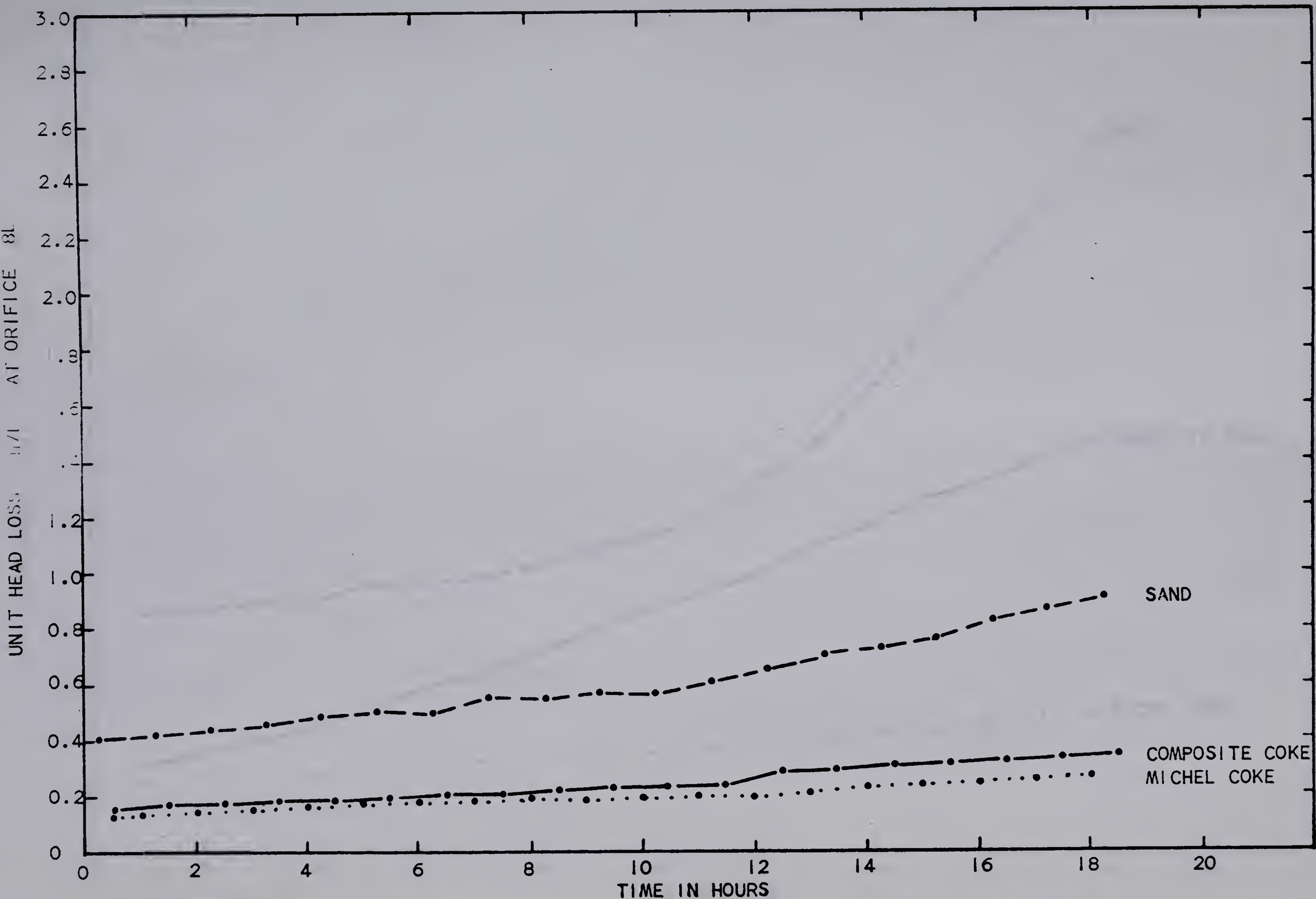


FIGURE 11: HEAD LOSS CURVES THREE FILTER MEDIA 2.4 U.S. GPM/SQ.FT.

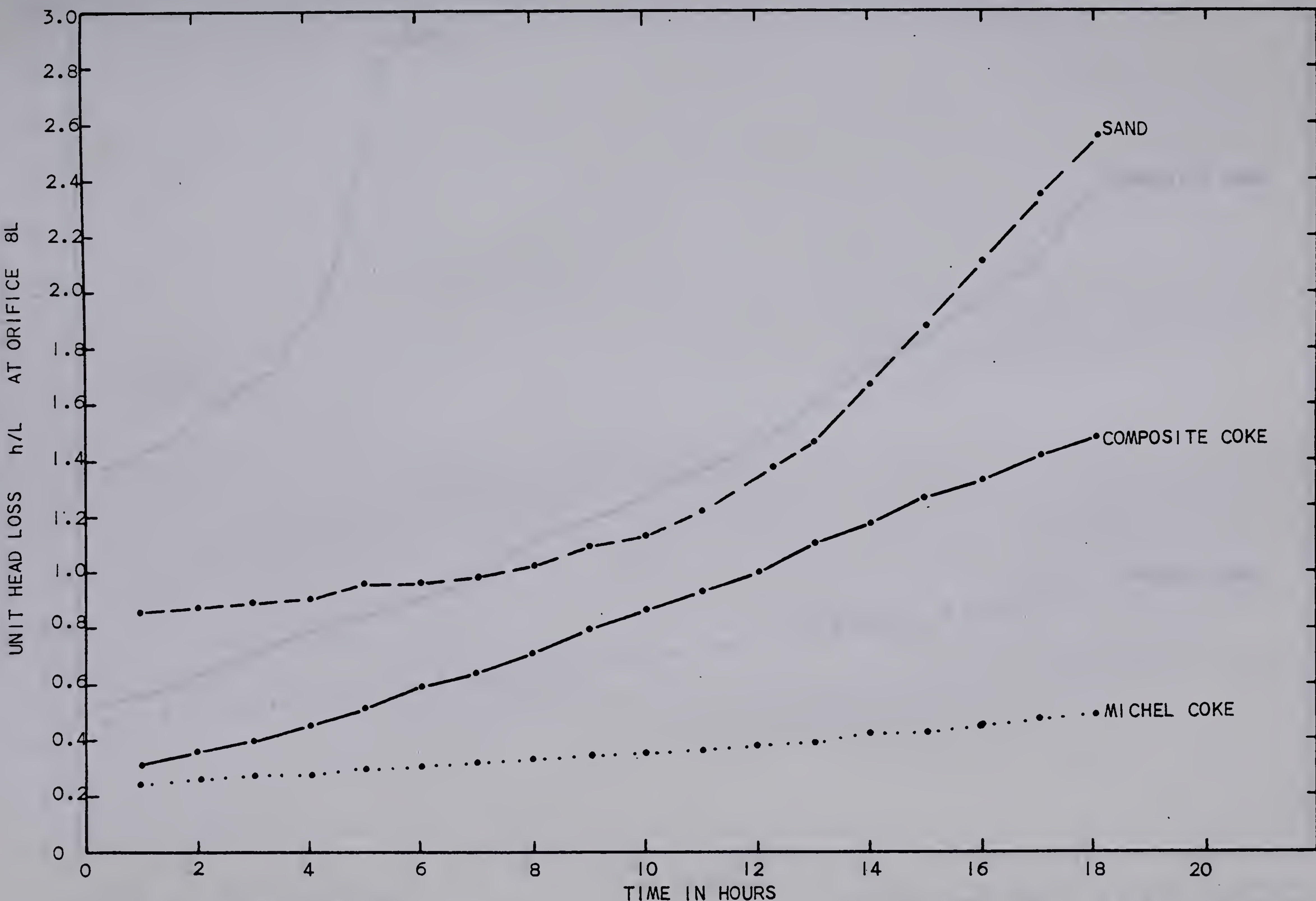
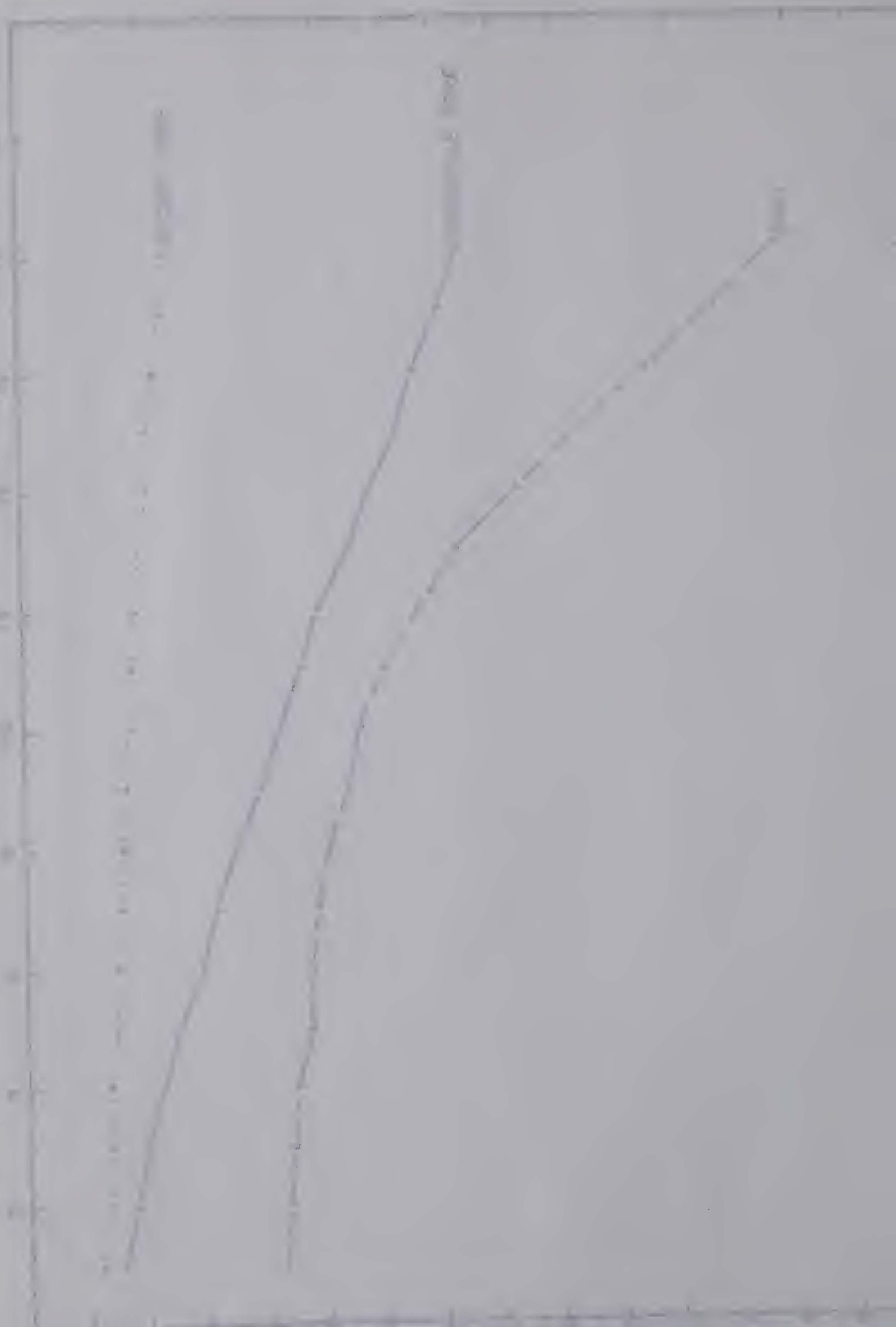


FIGURE 12: HEAD LOSS CURVES THREE FILTER MEDIA 5.0 U.S. GPM/SQ.FT.



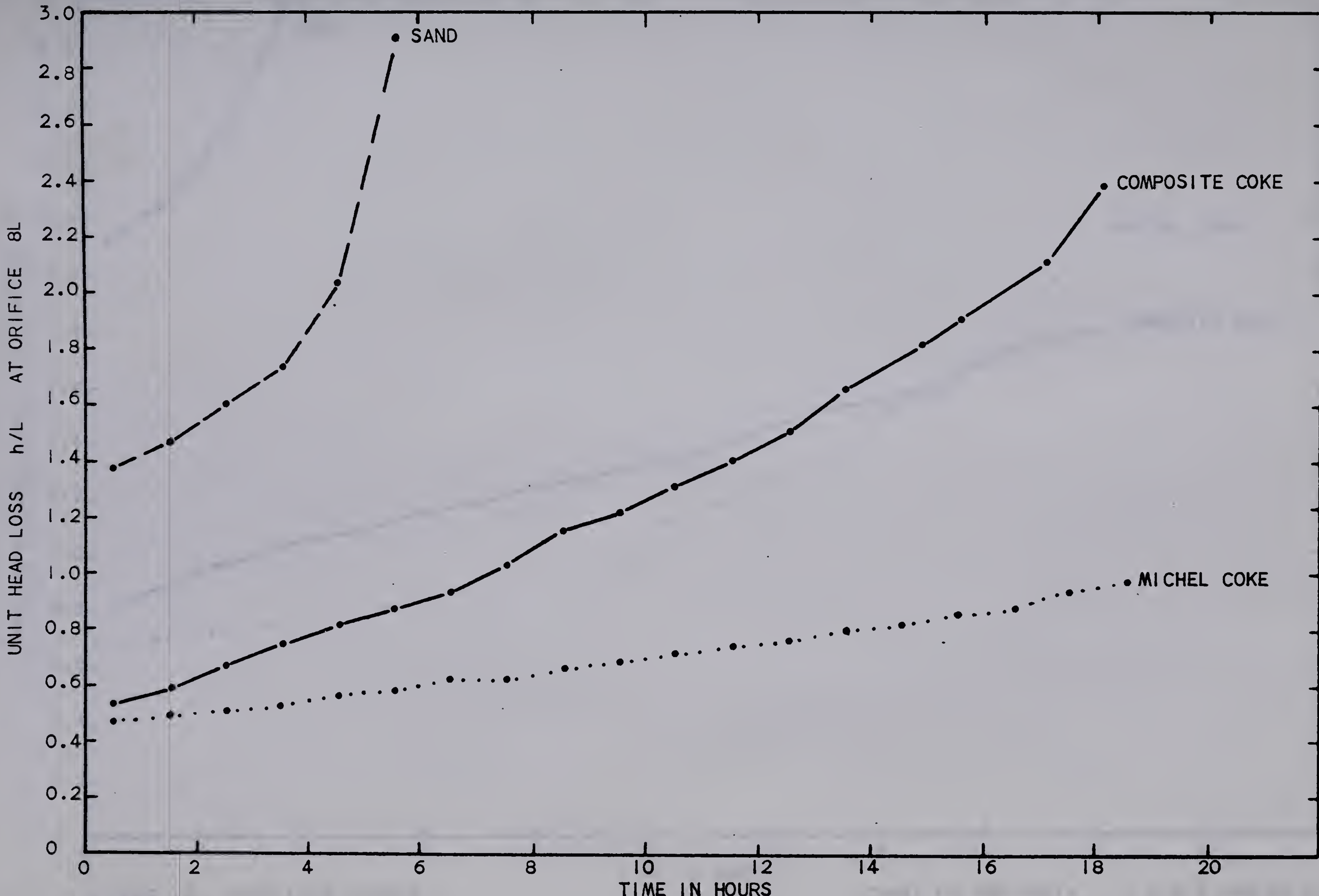
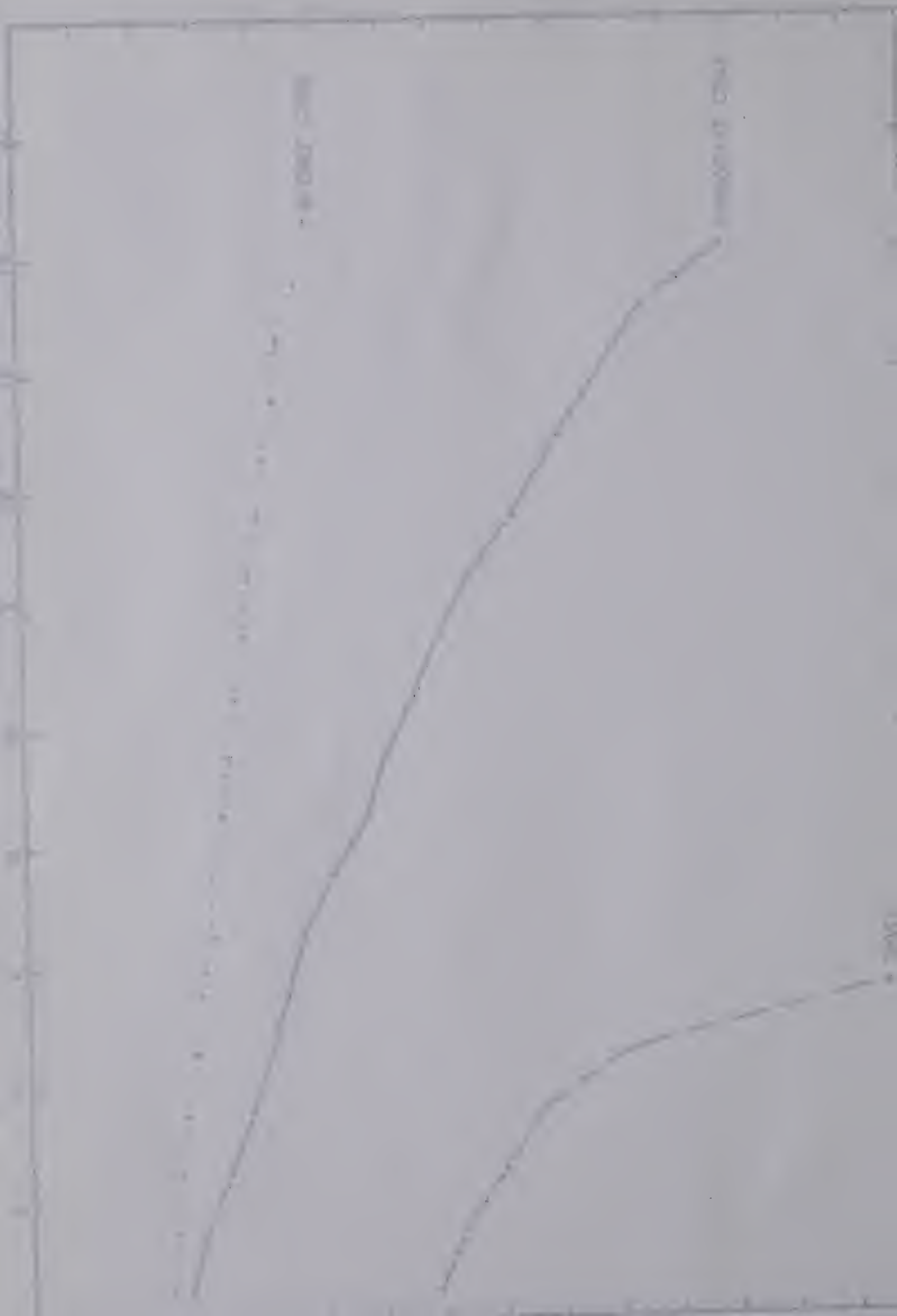


FIGURE 13: HEAD LOSS CURVES THREE FILTER MEDIA 8.5 U.S. GPM/SQ.FT.



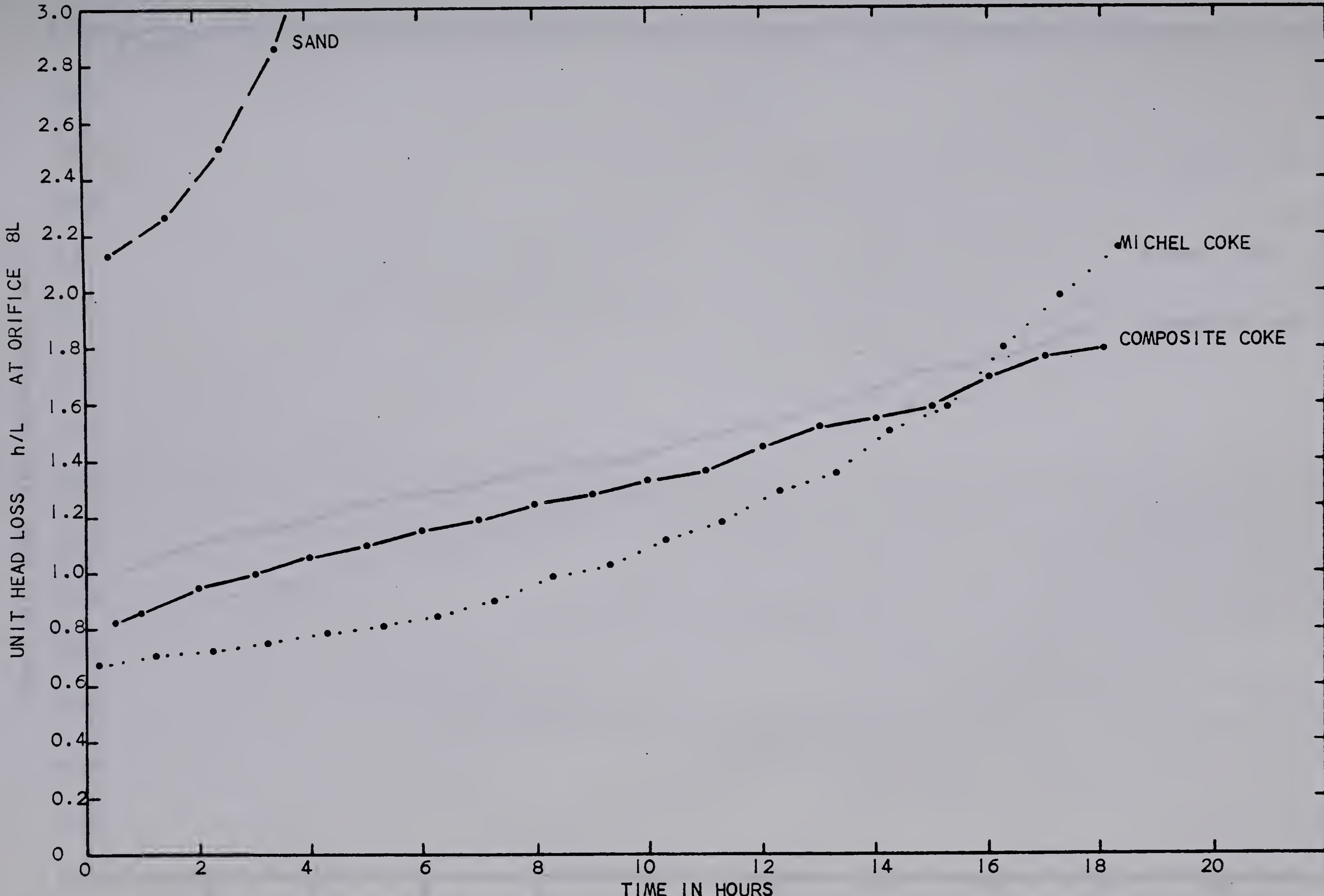
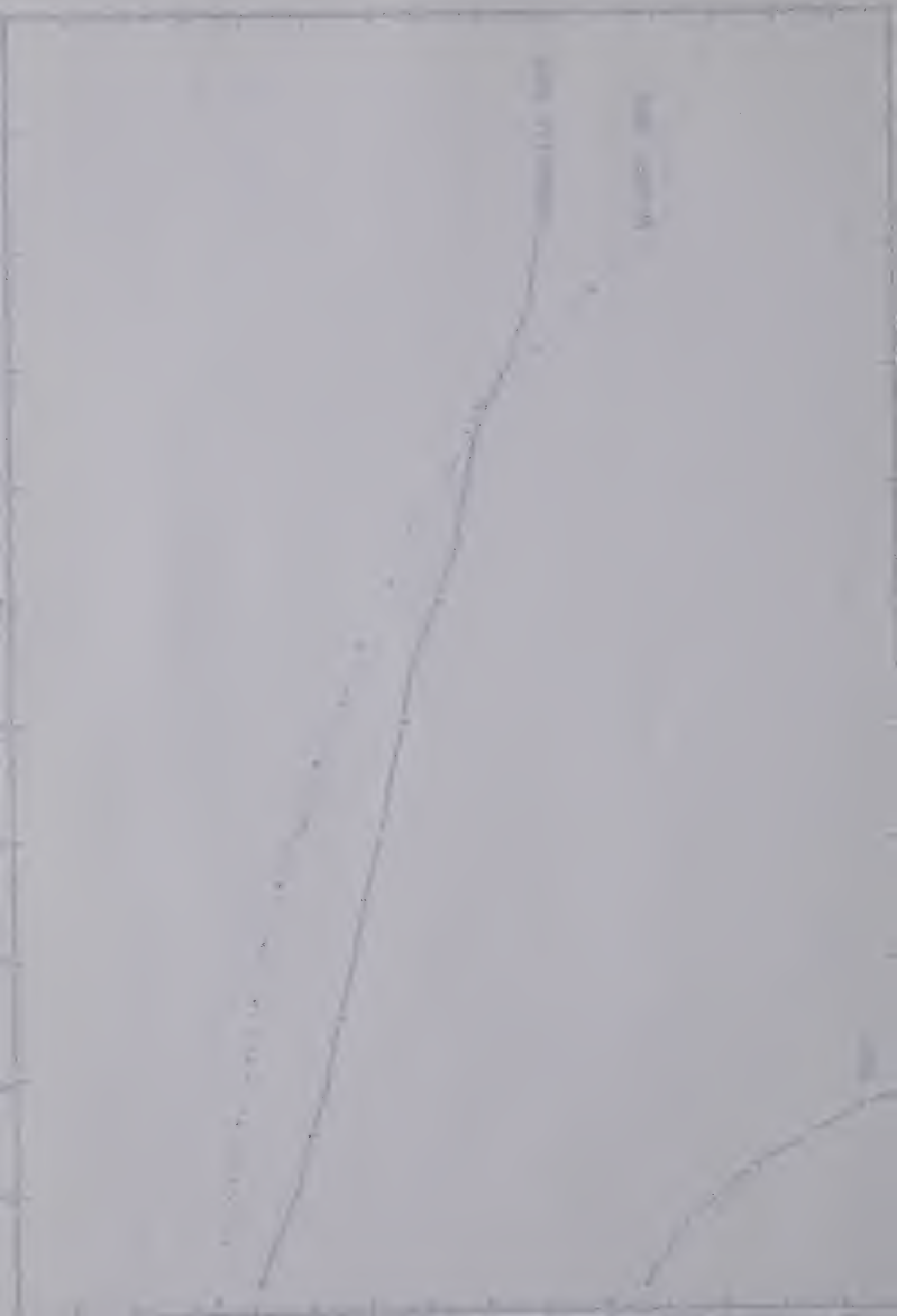


FIGURE 14: HEAD LOSS CURVES THREE FILTER MEDIA 12.0 U.S.GPM/SQ.FT.



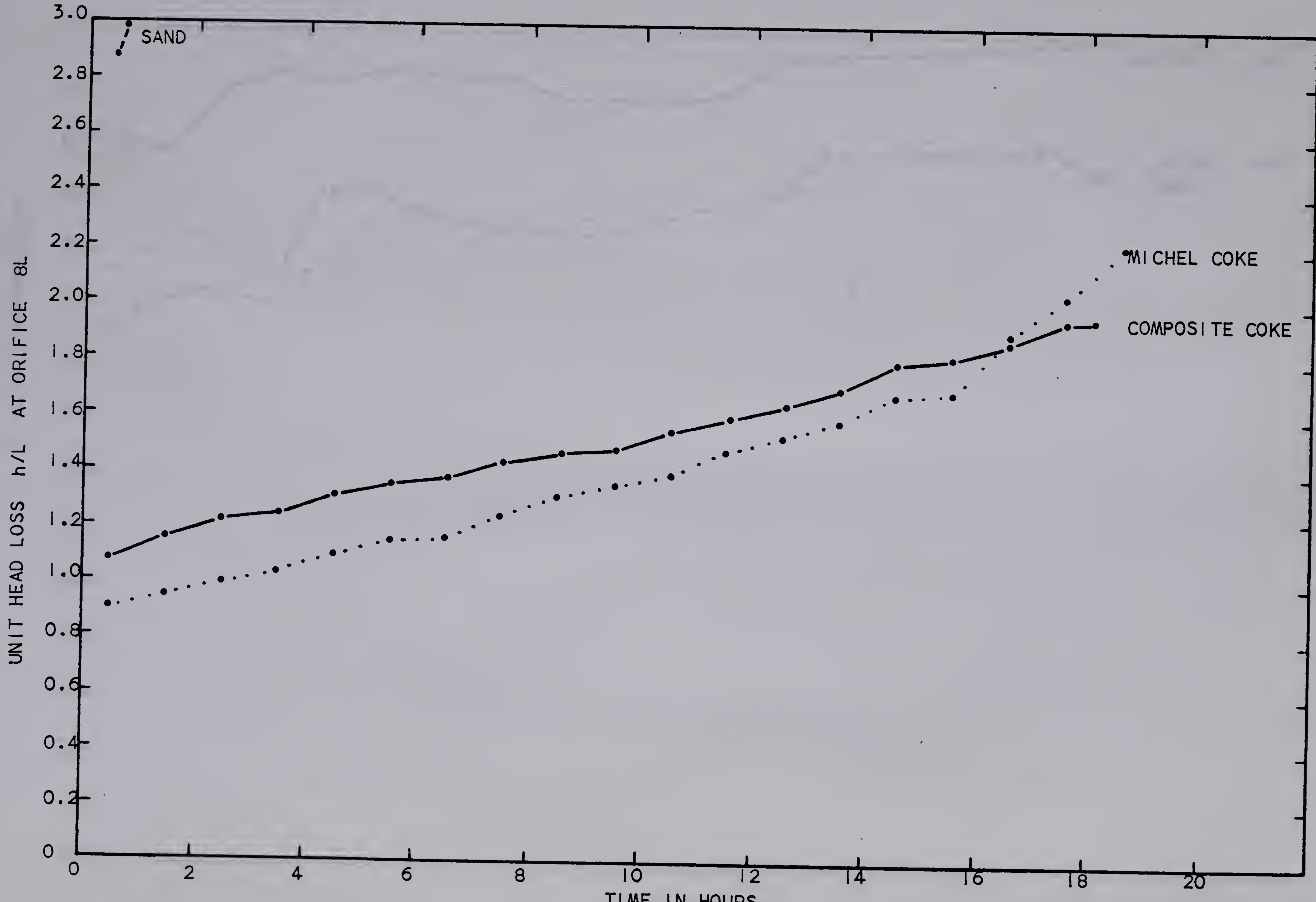


FIGURE 15: HEAD LOSS CURVES

THREE FILTER MEDIA 15.0 U.S.GPM/SQ.FT.

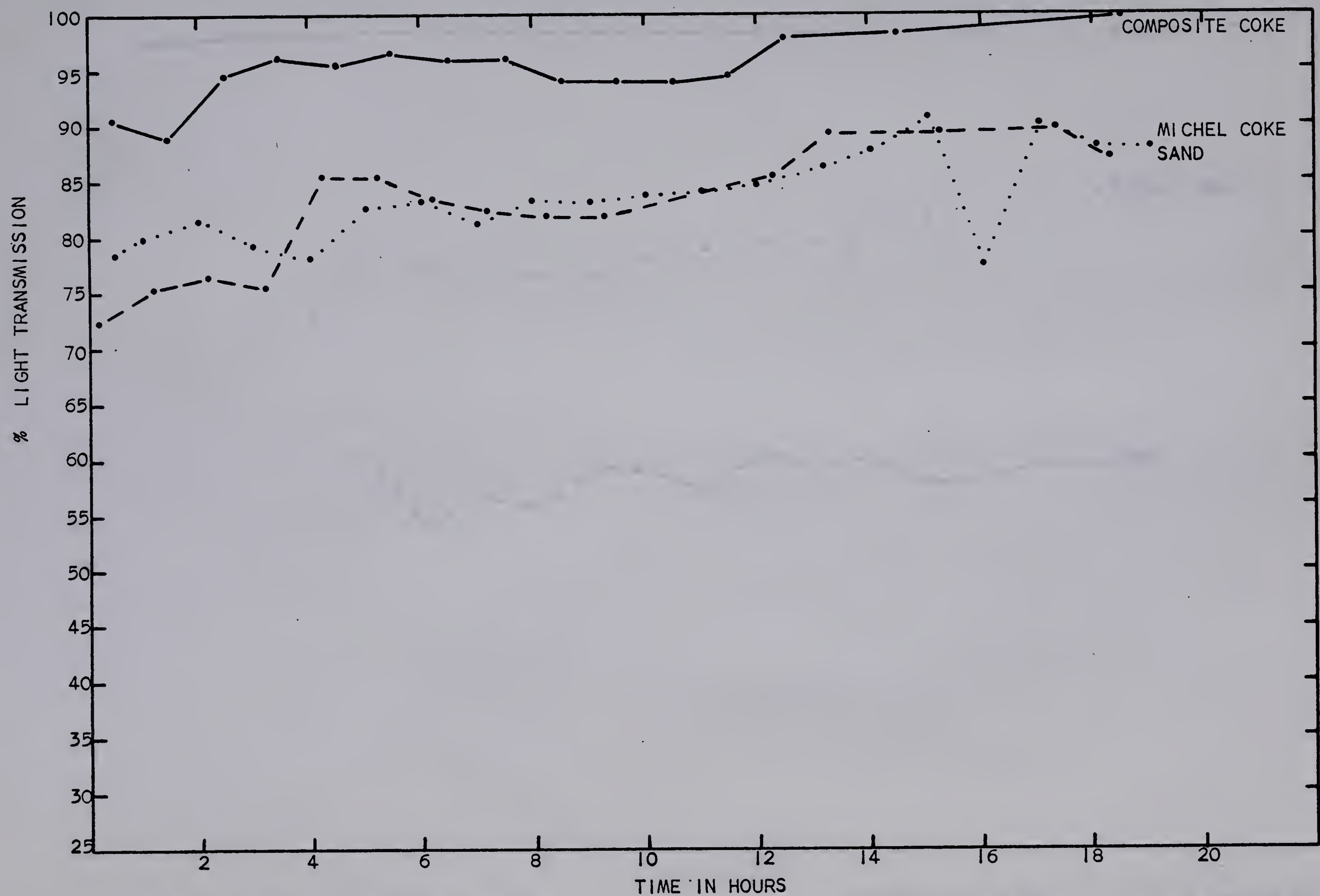


FIGURE 16: EFFLUENT TURBIDITY CURVES THREE FILTER MEDIA 2.4 U.S.GPM/SQ.FT.

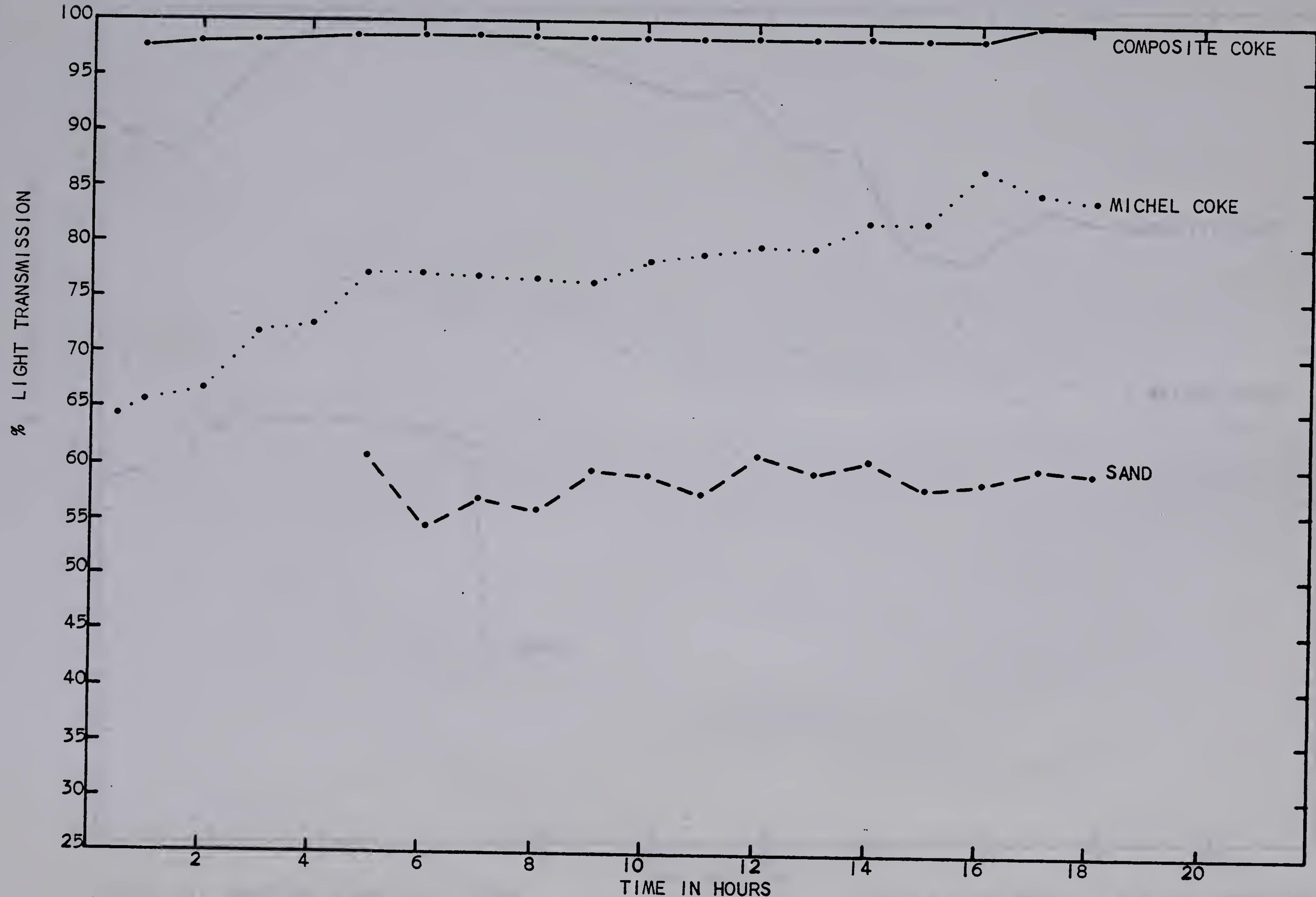
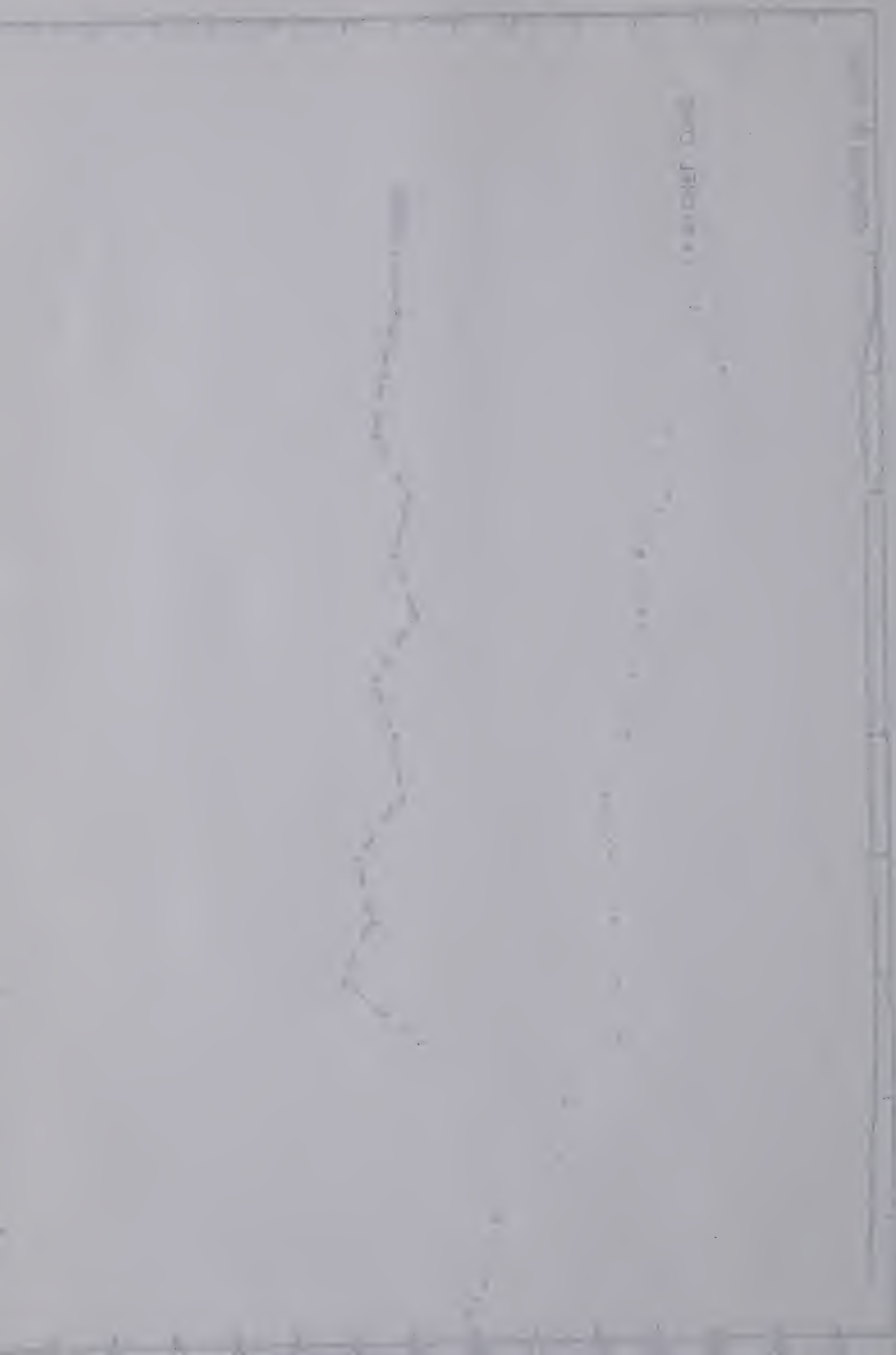


FIGURE 17: EFFLUENT TURBIDITY CURVES

THREE FILTER MEDIA 5.0 U.S.GPM/SQ.FT.



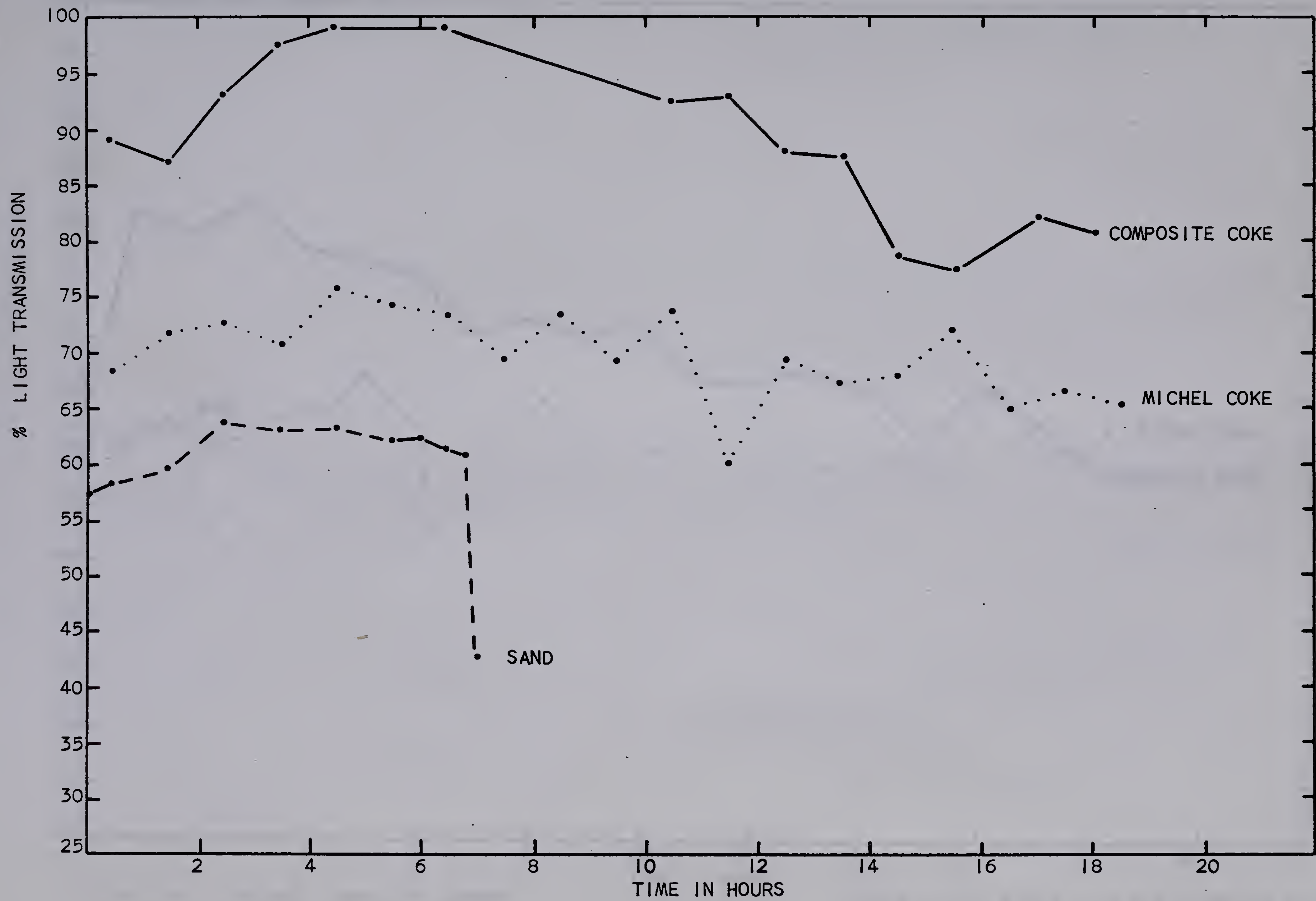


FIGURE 18: EFFLUENT TURBIDITY CURVES THREE FILTER MEDIA 8.5 U.S.GPM/SQ.FT.

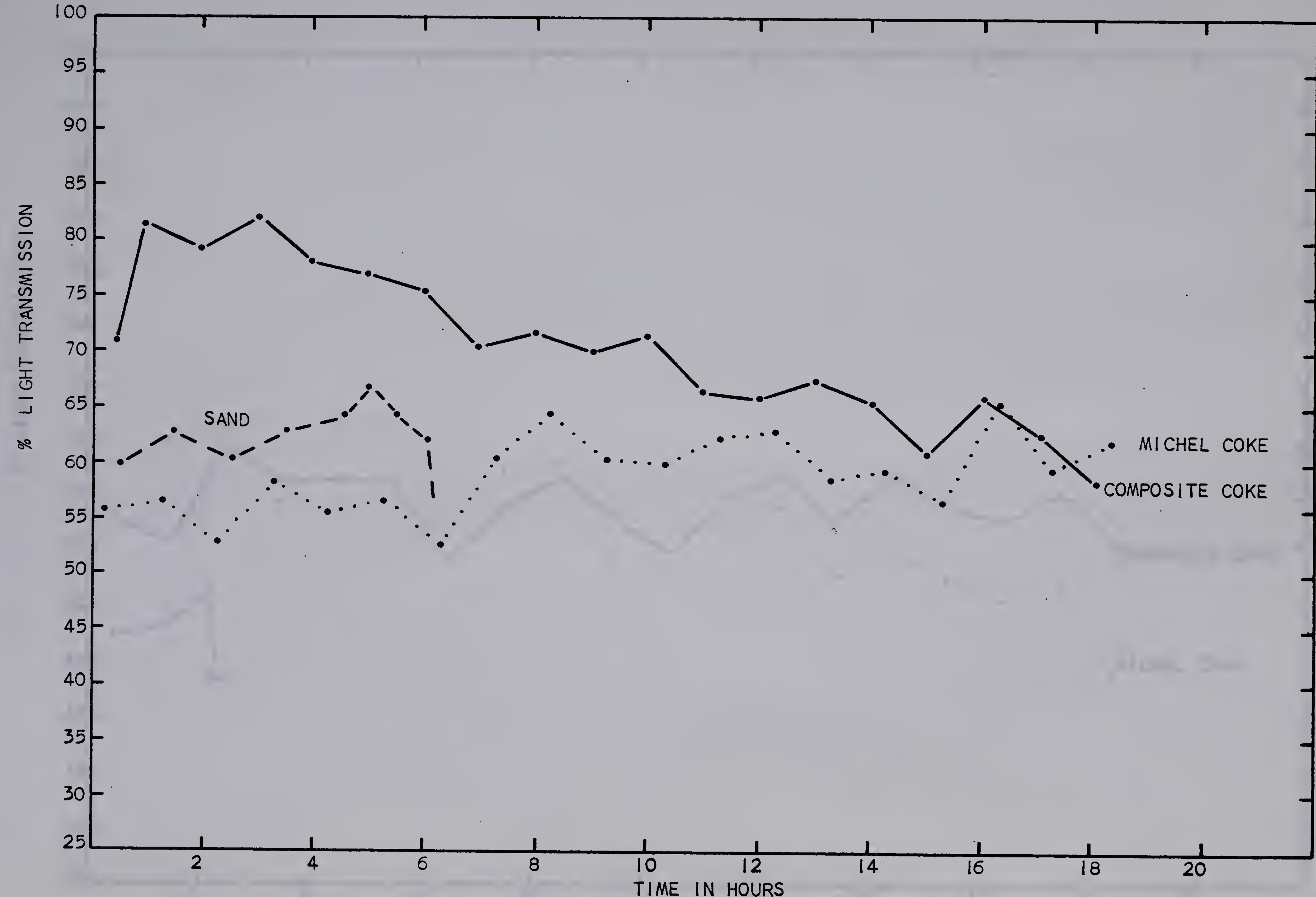
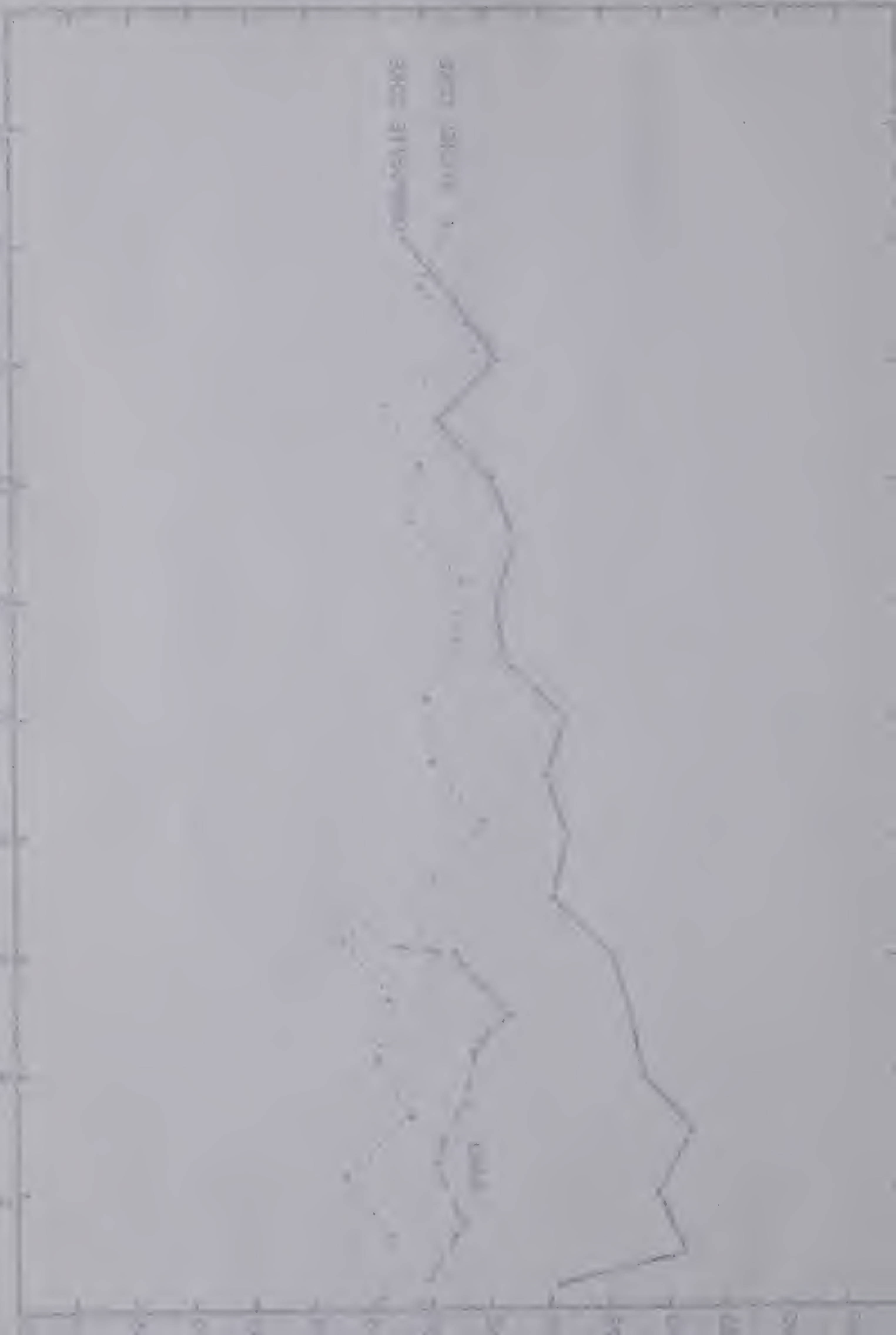


FIGURE 19: EFFLUENT TURBIDITY CURVES THREE FILTER MEDIA 12.0 U.S.GPM/SQ.FT.



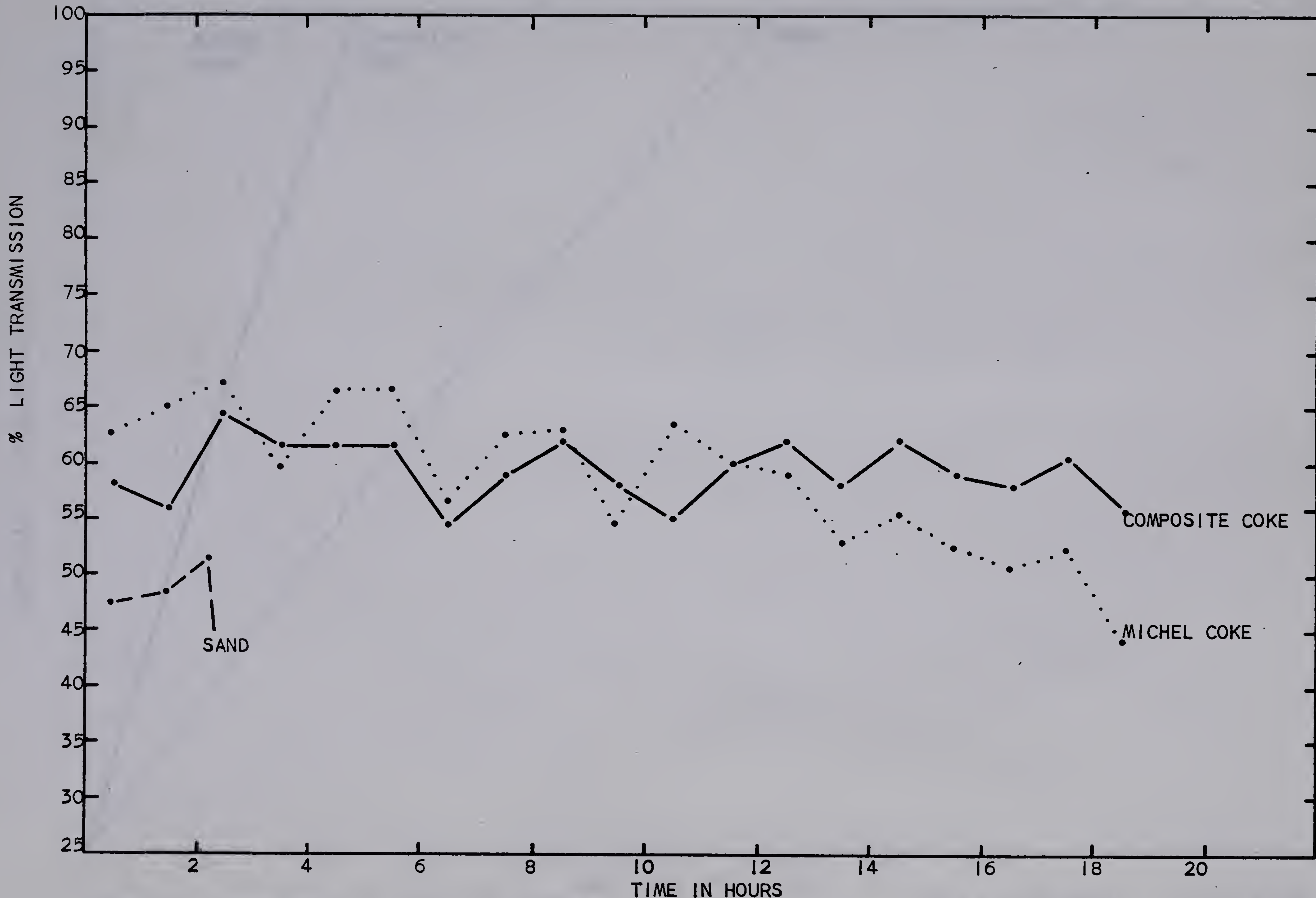


FIGURE 20: EFFLUENT TURBIDITY CURVES THREE FILTER MEDIA 15.0 U.S.GPM/SQ.FT.

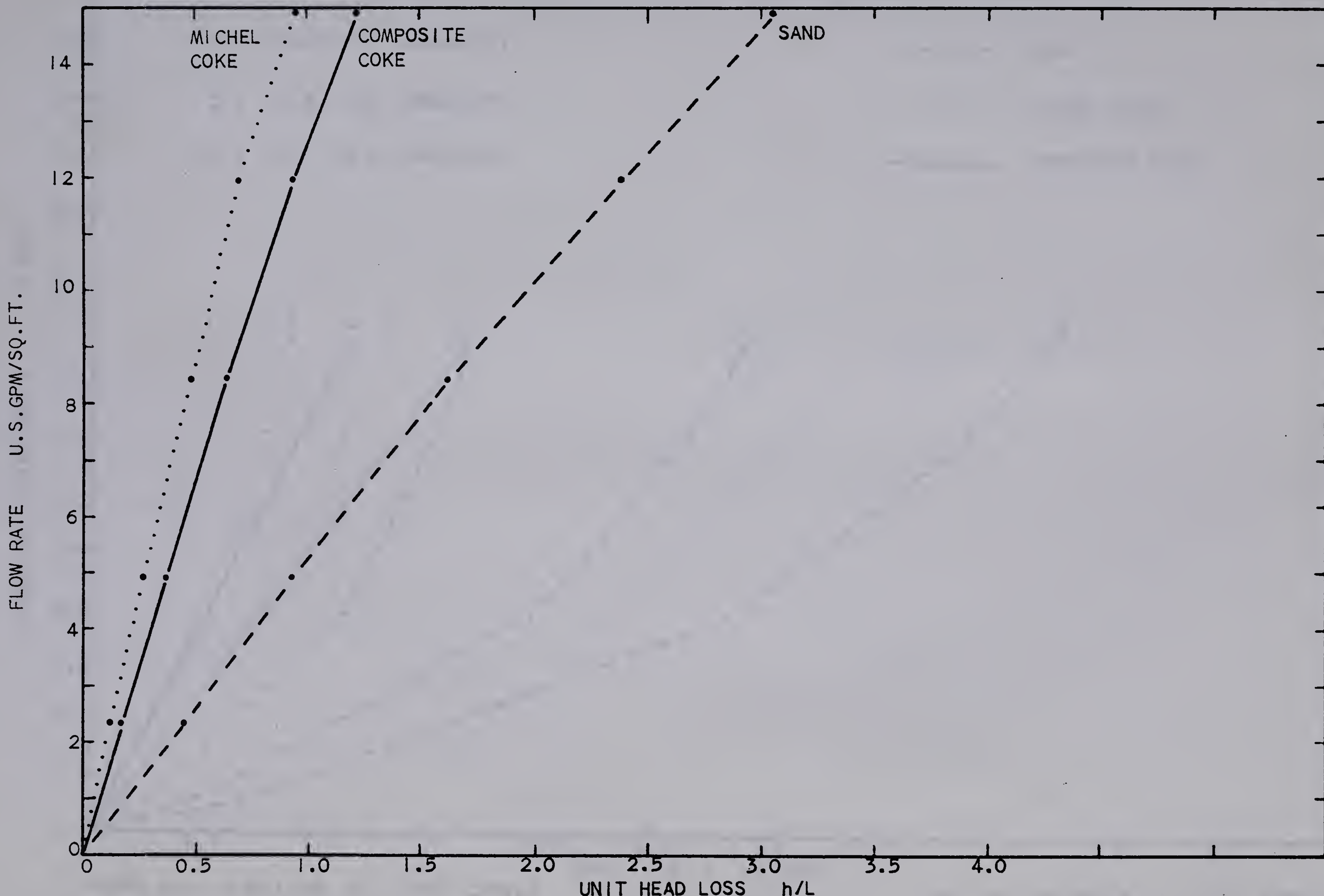


FIGURE 21: HEAD LOSS VS FLOW RATE CURVES THREE FILTER MEDIA CLEAR WATER

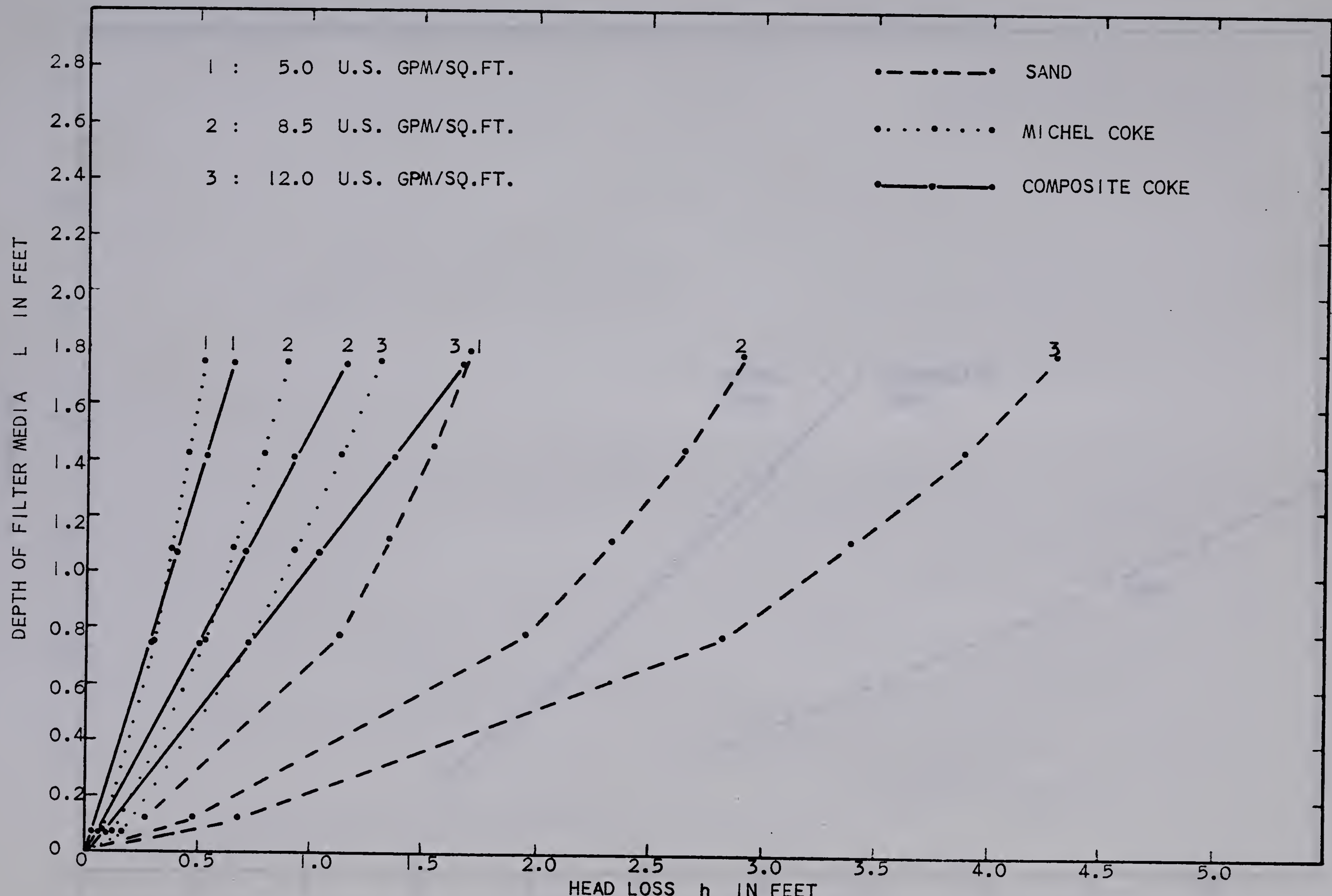


FIGURE 22: HEAD LOSS VS DEPTH CURVES THREE FILTER MEDIA CLEAR WATER

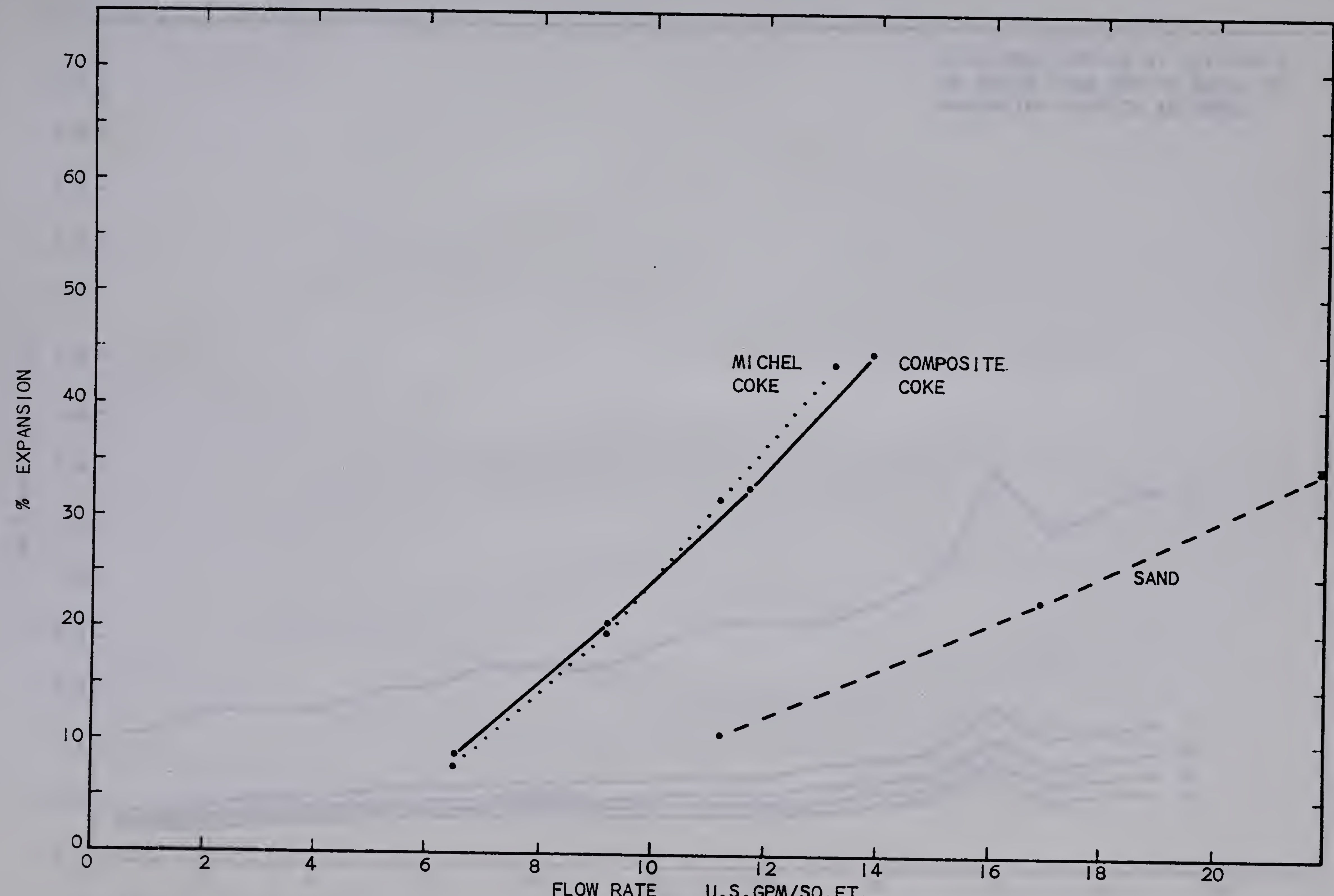


FIGURE 23: FILTER WASH CURVES

THREE FILTER MEDIA

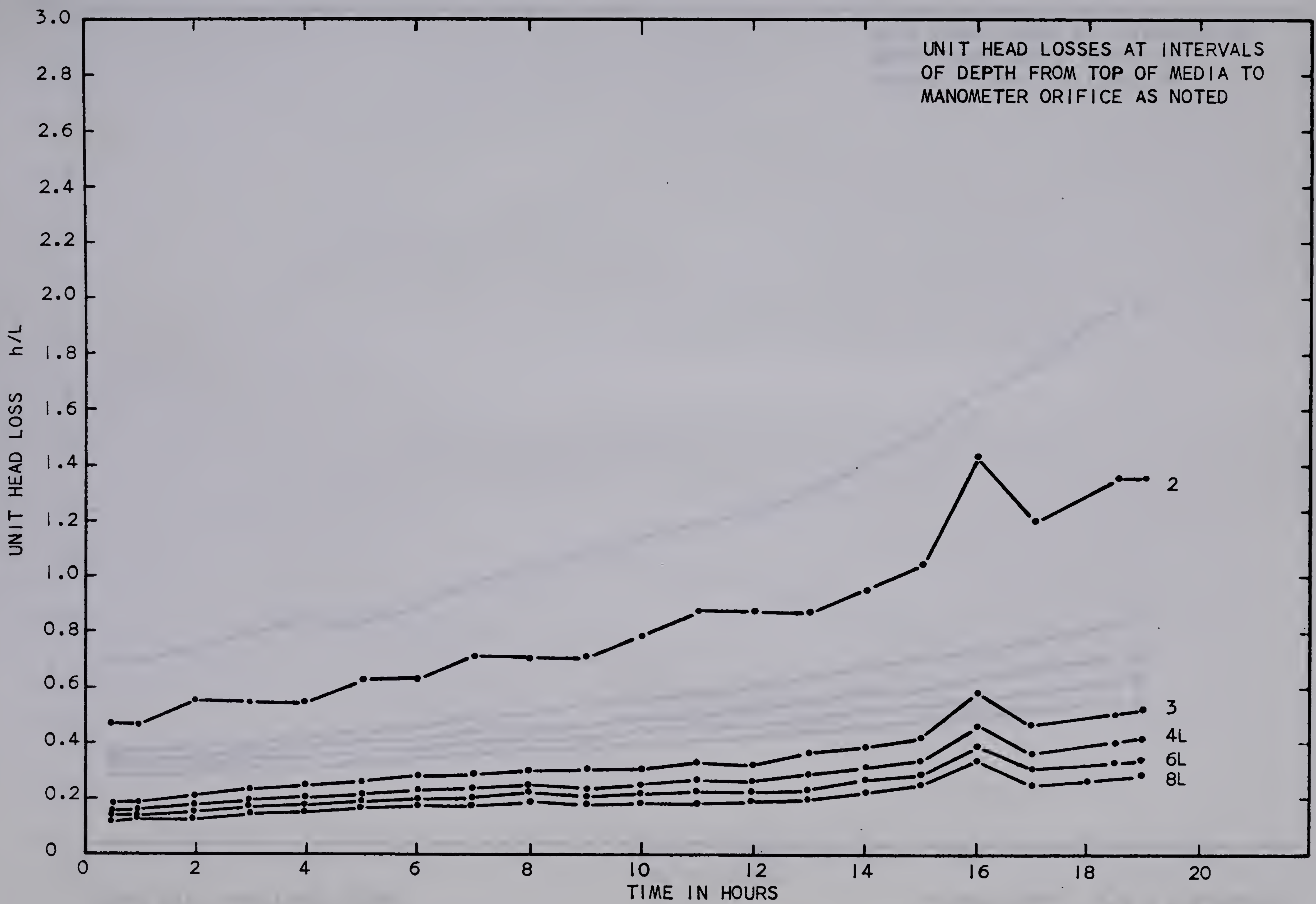


FIGURE 24: HEAD LOSS CURVES

MICHEL COKE · 2.4 U.S. GPM/SQ.FT.

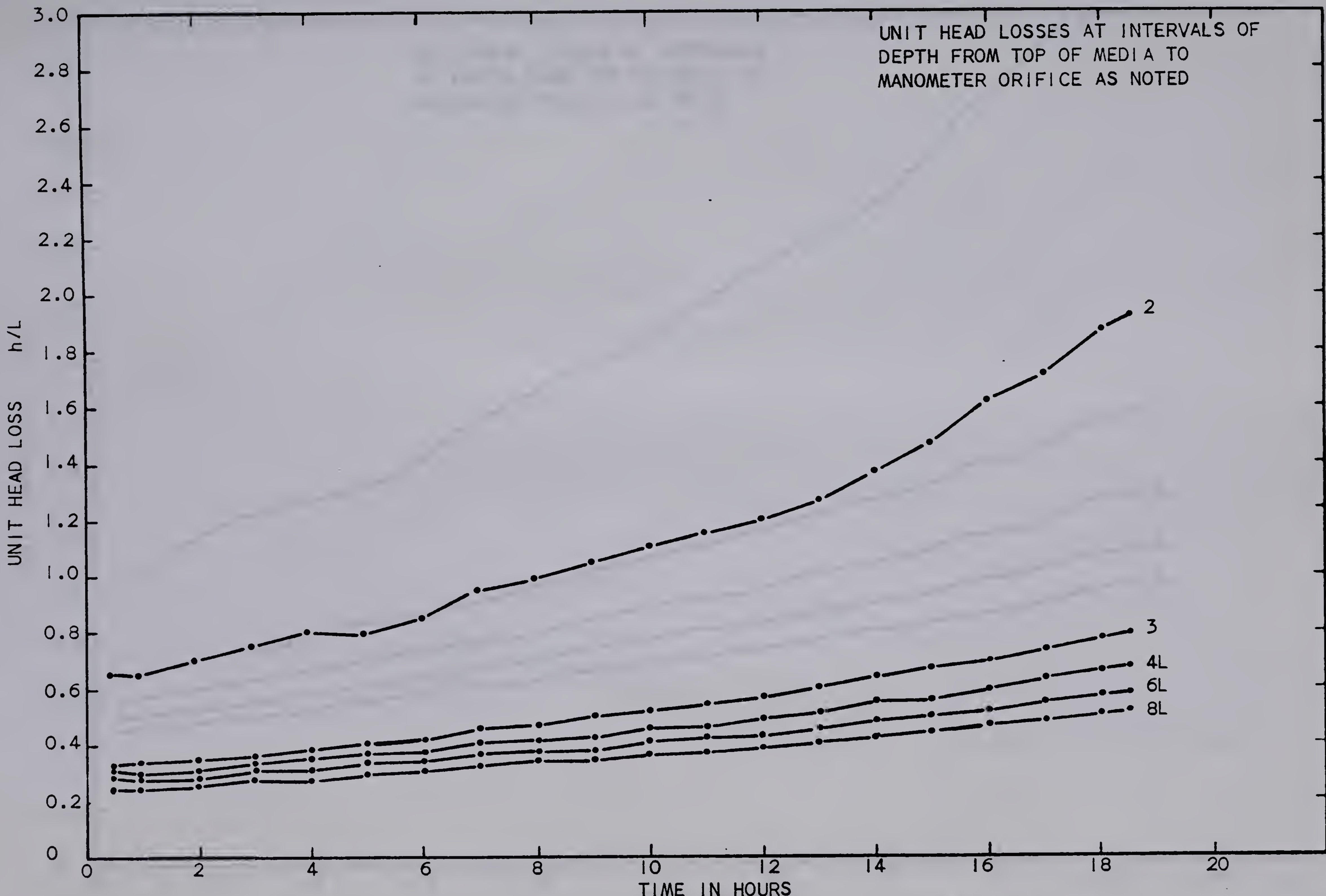


FIGURE 25: HEAD LOSS CURVES

MICHEL COKE 5.0 U.S.GPM/SQ.FT.

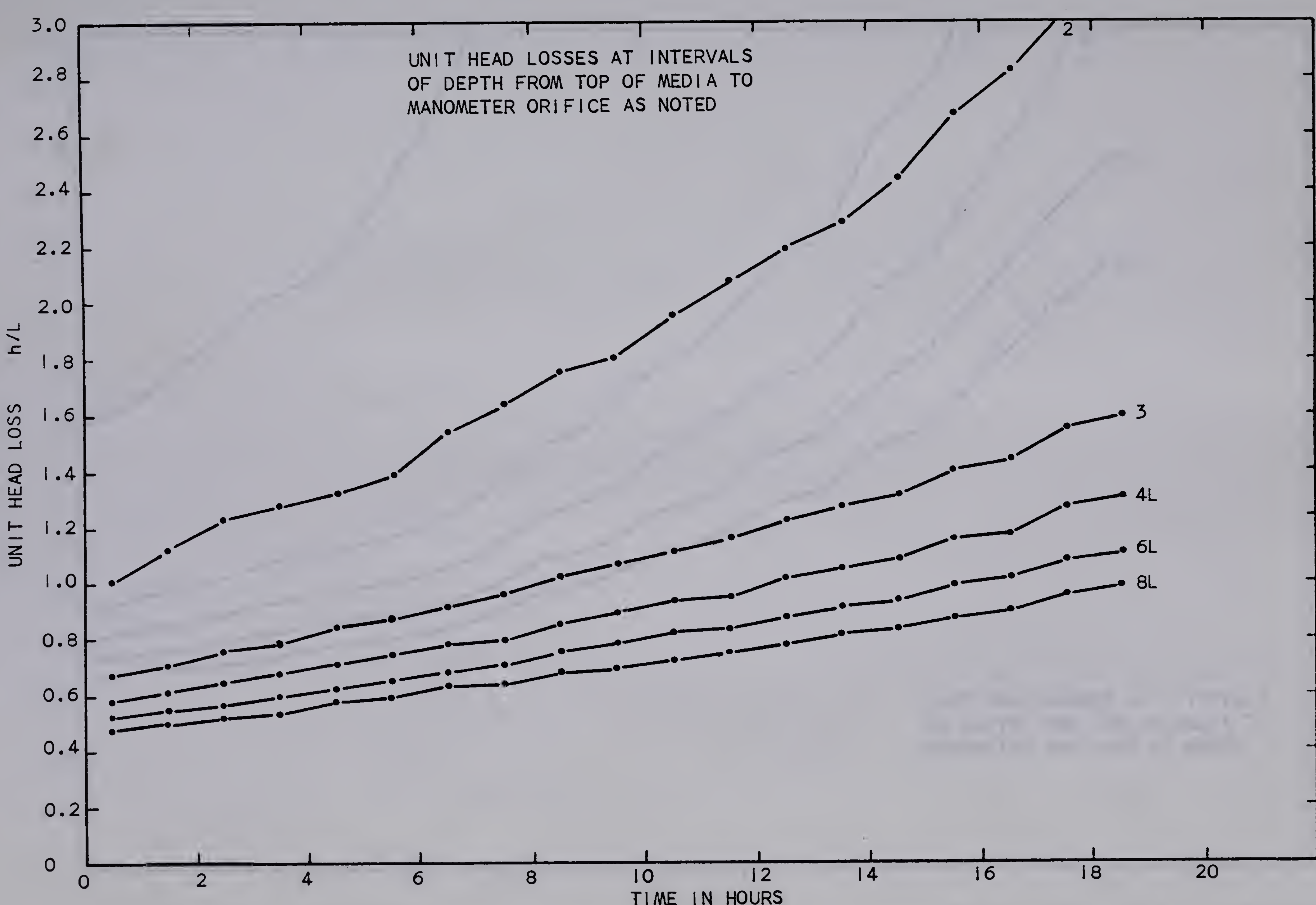
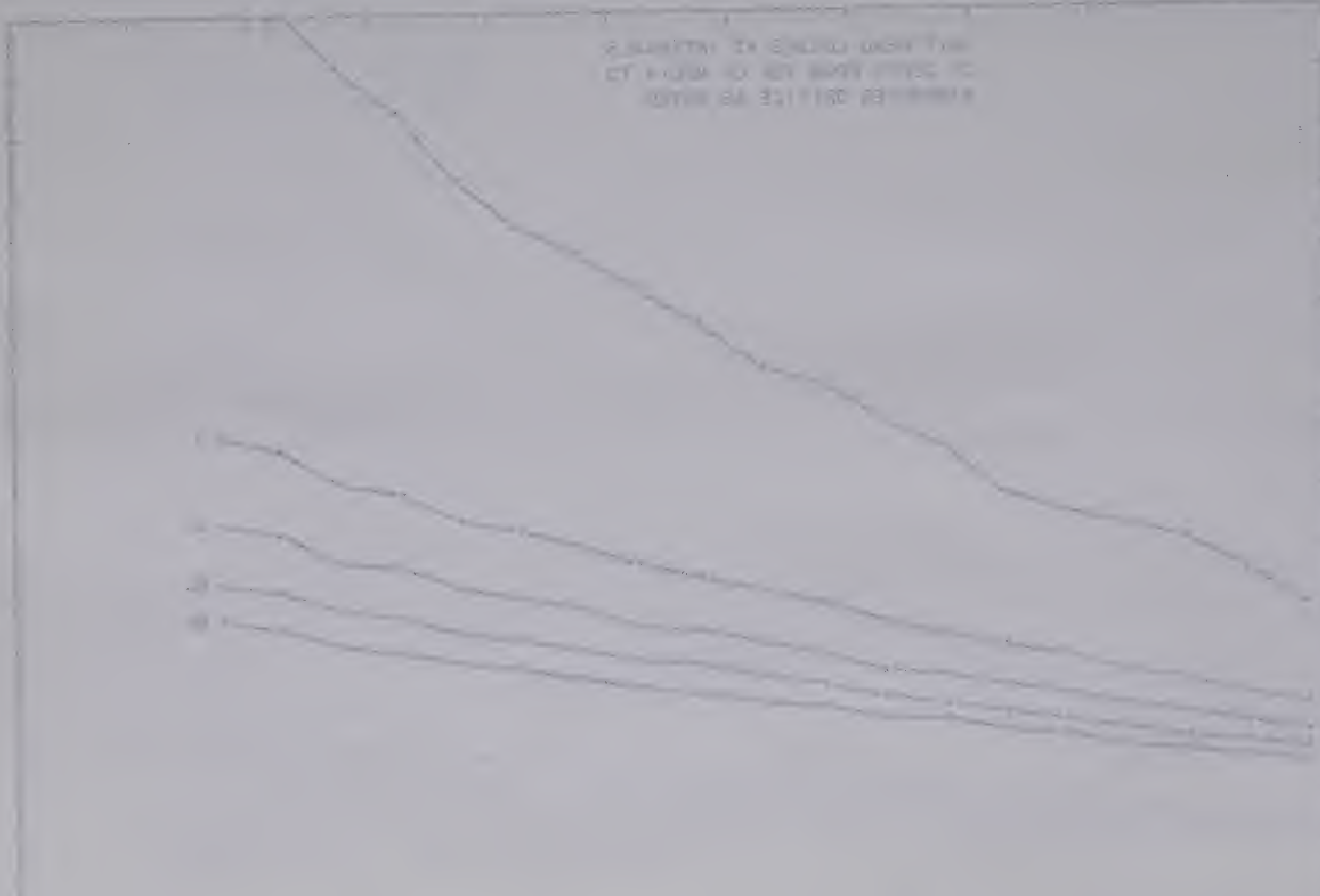


FIGURE 26: HEAD LOSS CURVES

MICHEL COKE 8.5 U.S.GPM/SQ.FT.



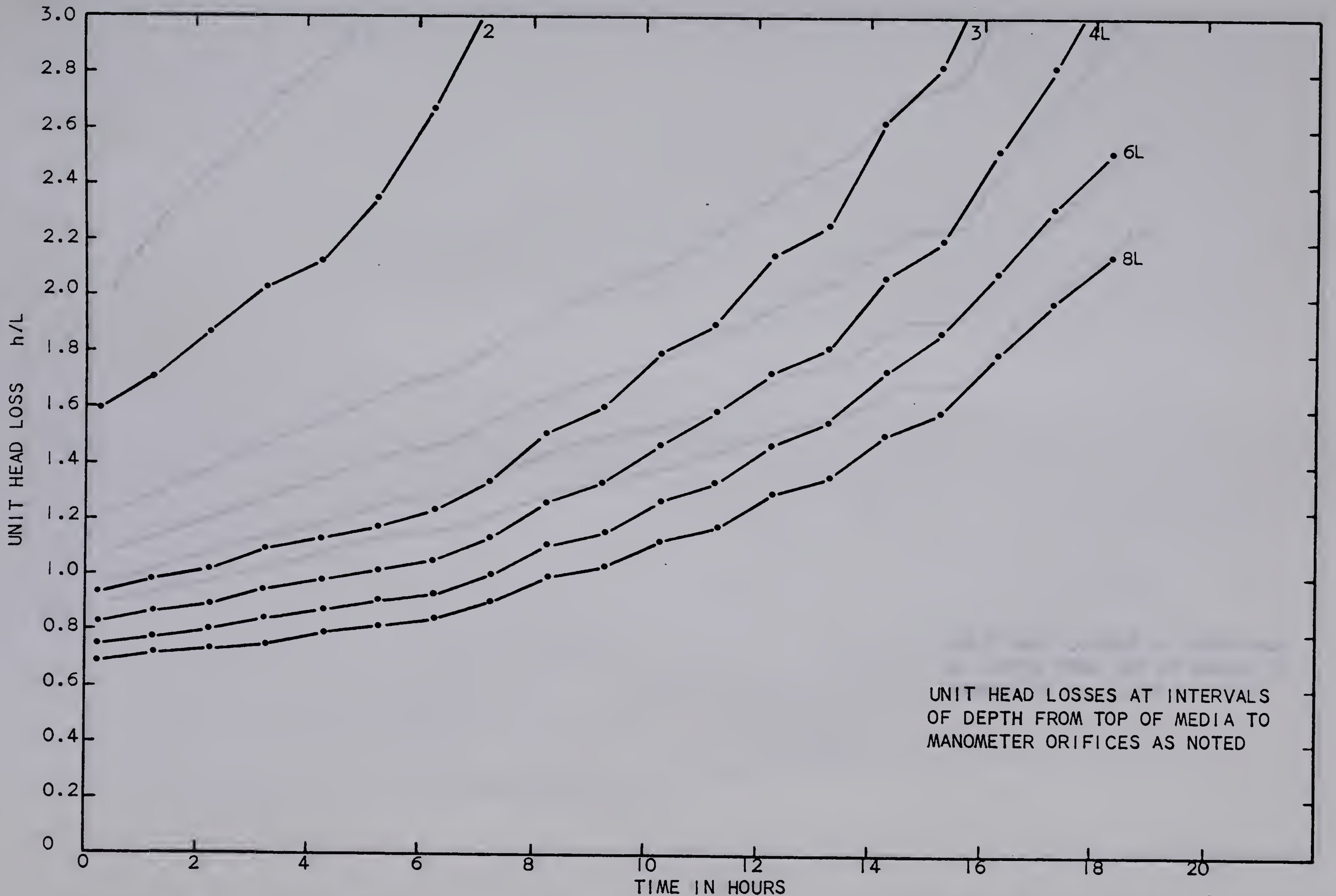
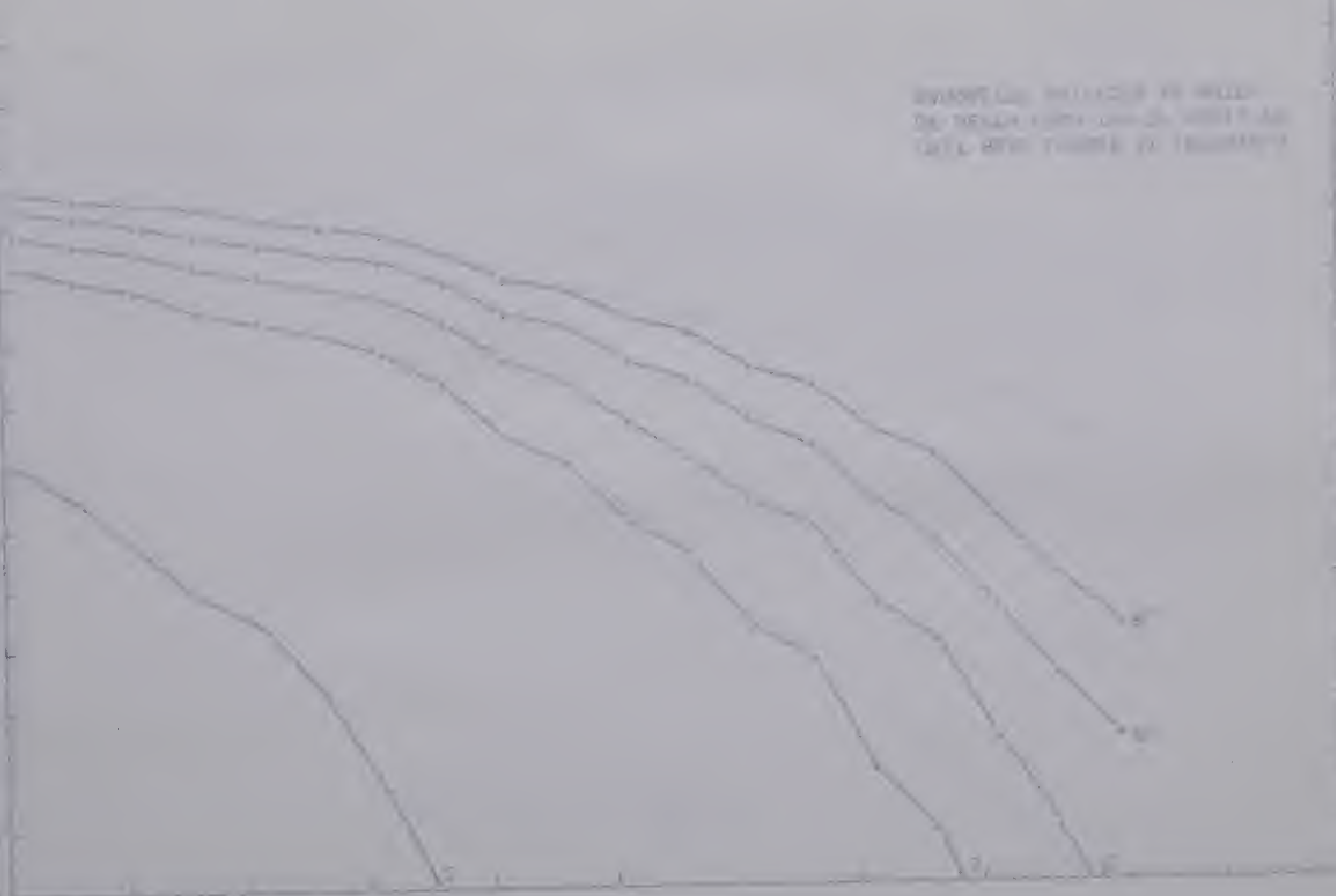


FIGURE 27: HEAD LOSS CURVES

MICHEL COKE 12.0 U.S.GPM/SQ.FT.



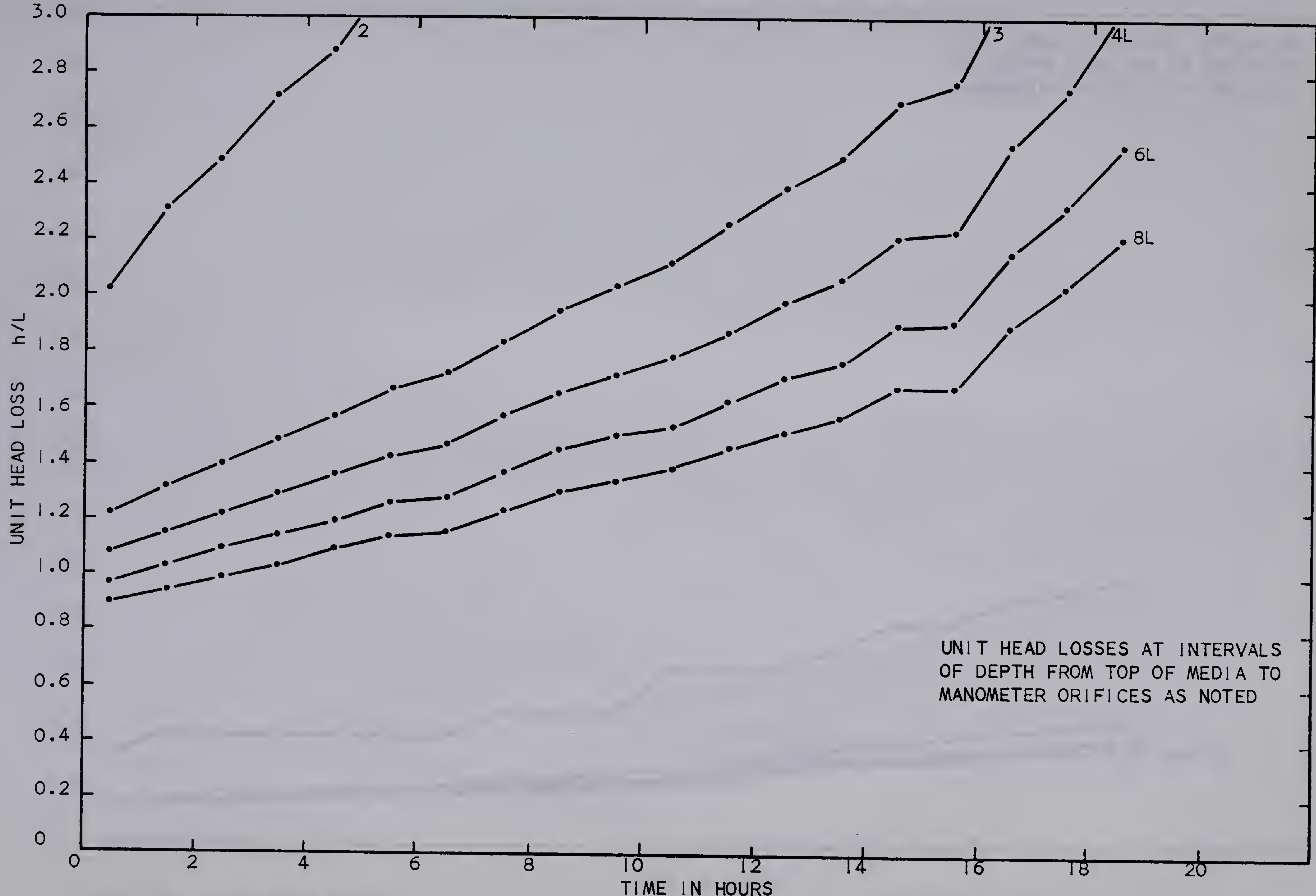
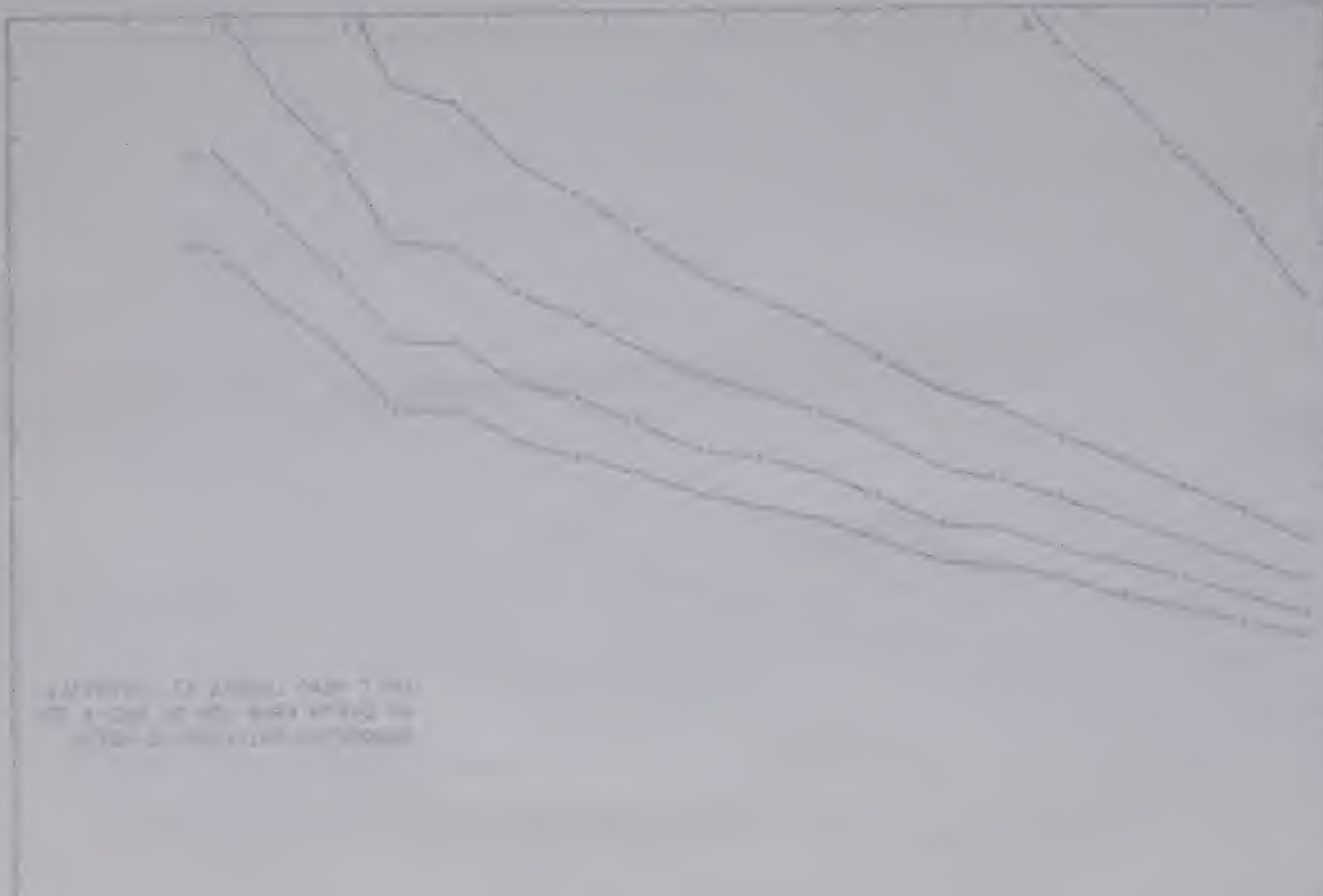


FIGURE 28: HEAD LOSS CURVES

MICHEL COKE 15.0 U.S.GPM/SQ.FT.



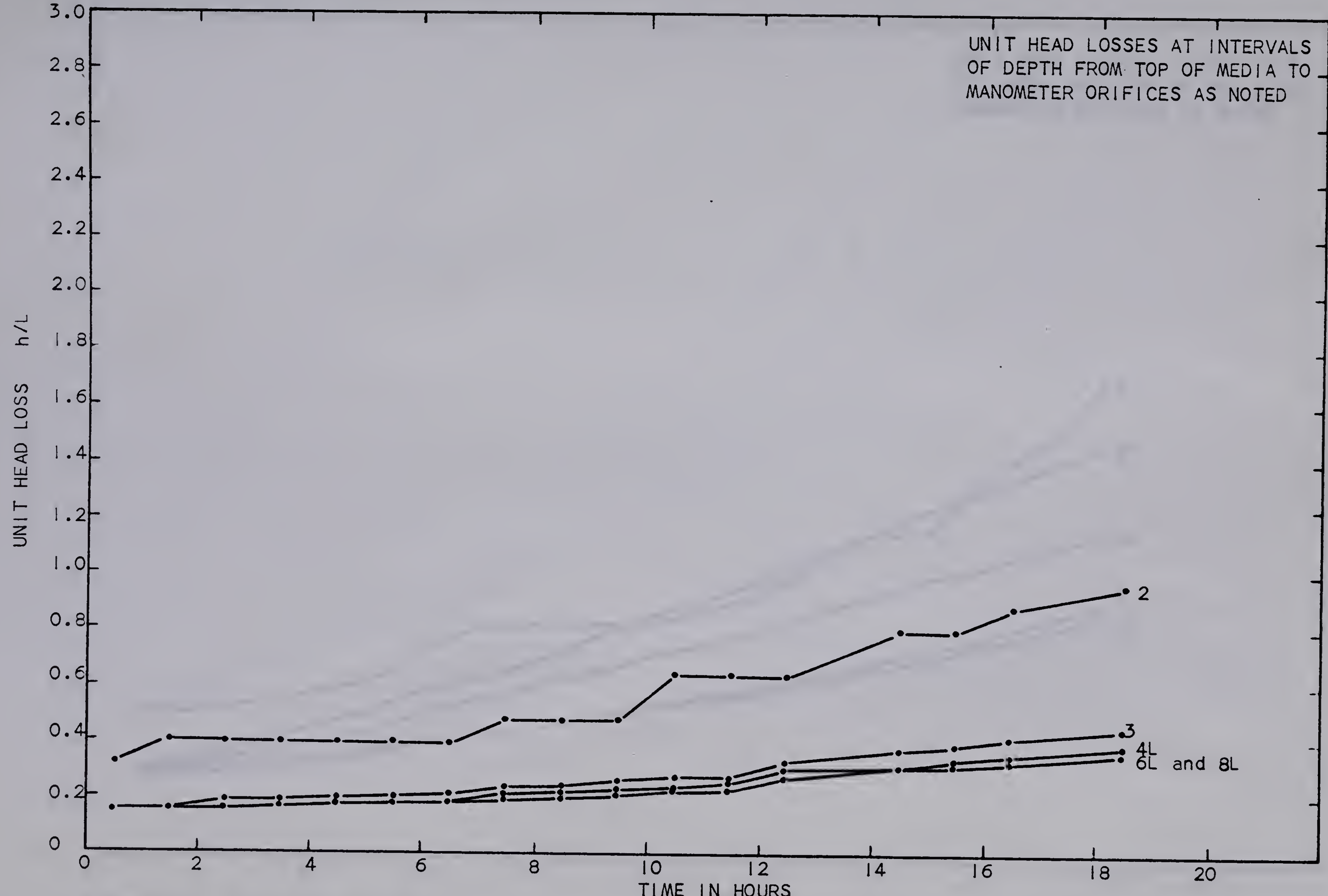


FIGURE 29: HEAD LOSS CURVES

COMPOSITE COKE 2.4 U.S.GPM/SQ.FT.

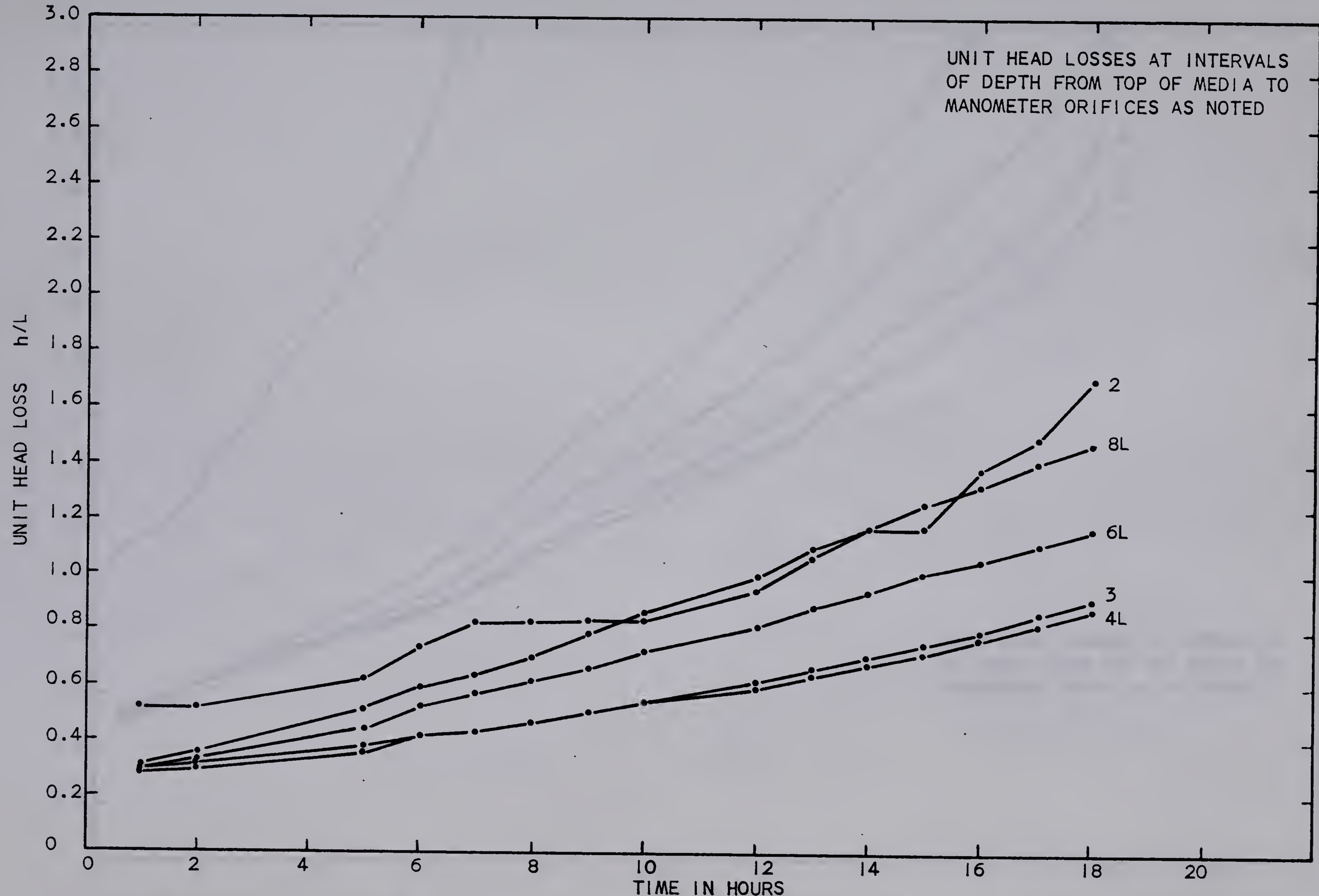


FIGURE 30: HEAD LOSS CURVES

COMPOSITE COKE 5.0 U.S.GPM/SQ.FT.

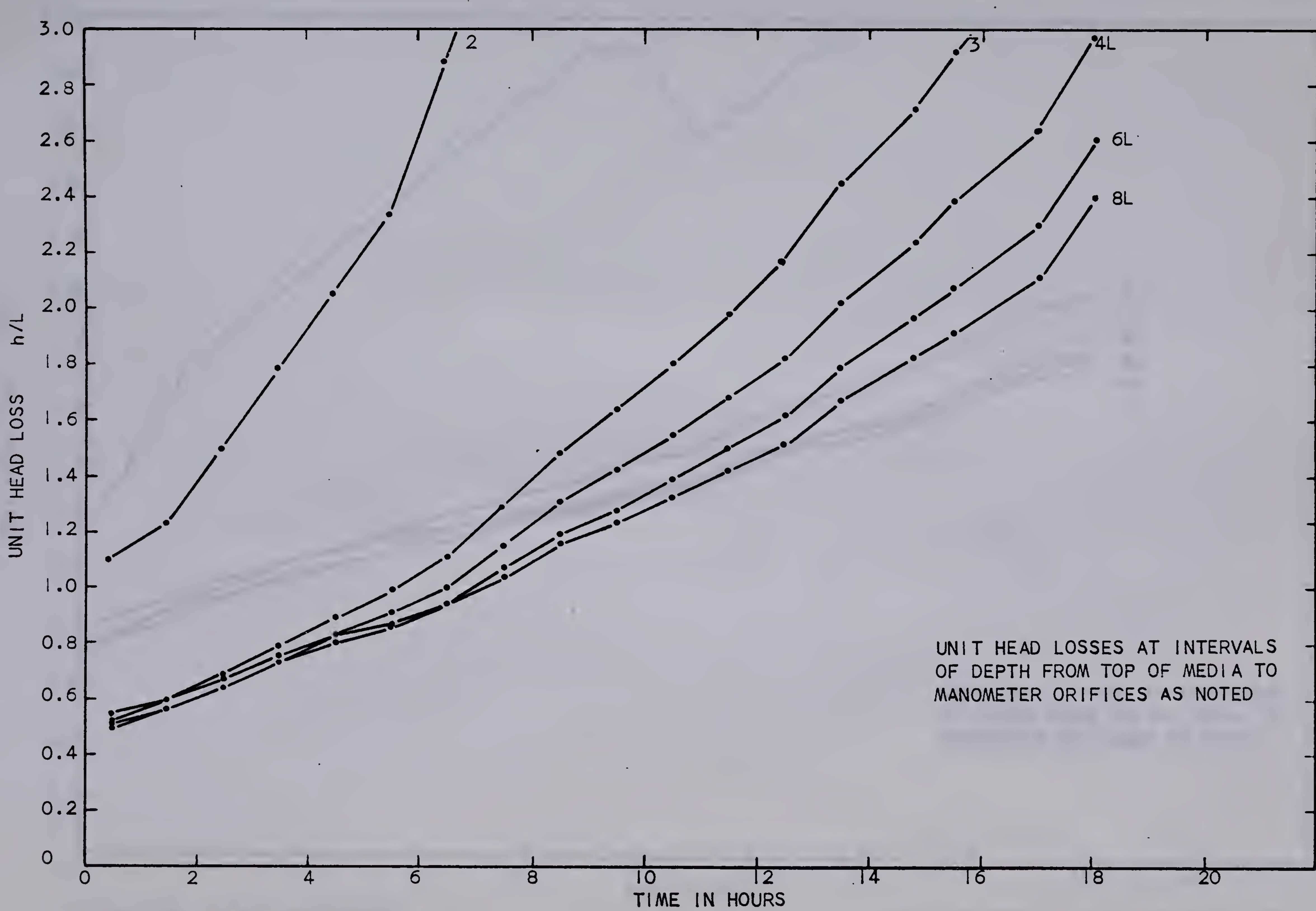
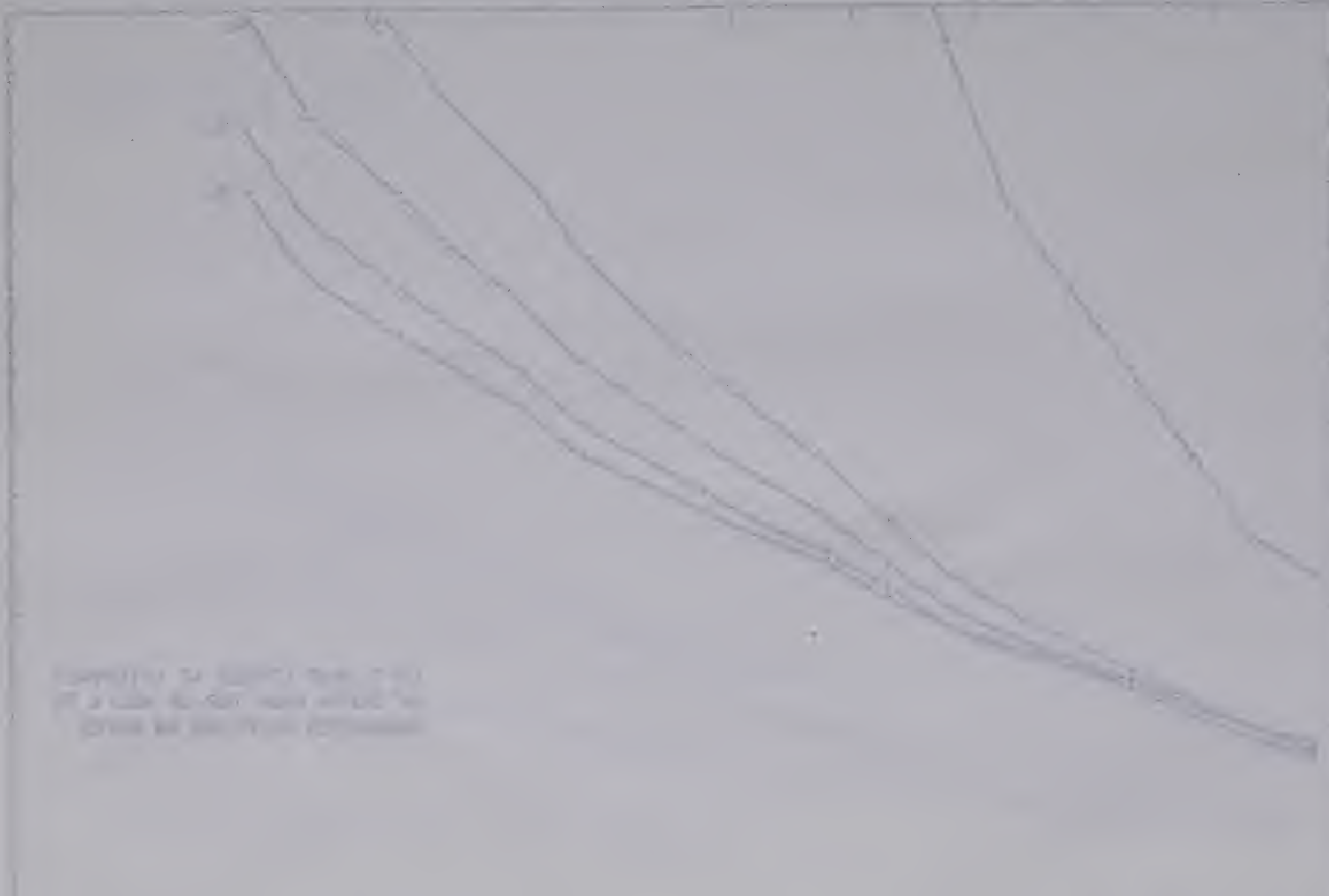


FIGURE 31: HEAD LOSS CURVES COMPOSITE COKE 8.5 U.S. GPM/SQ.FT.



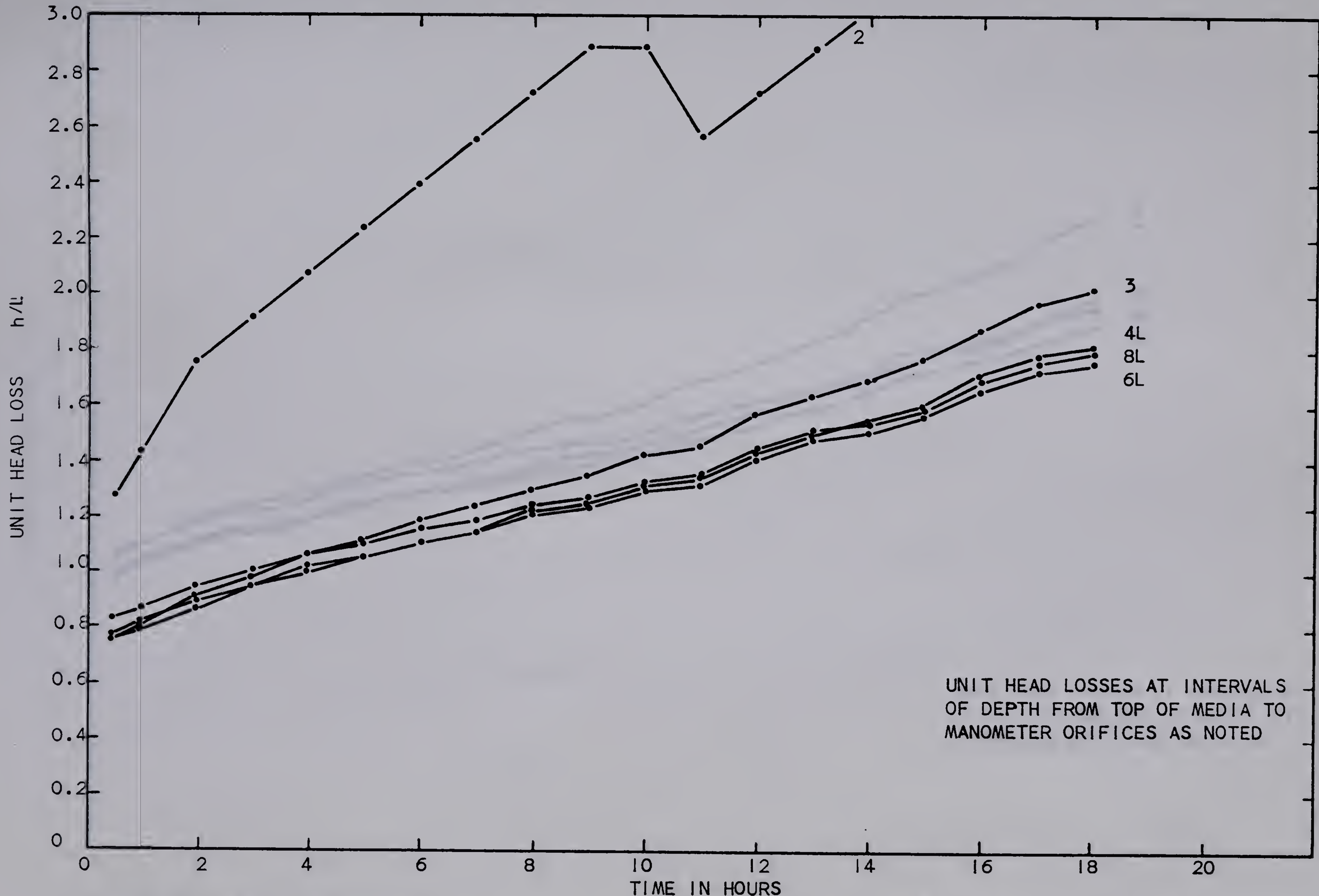
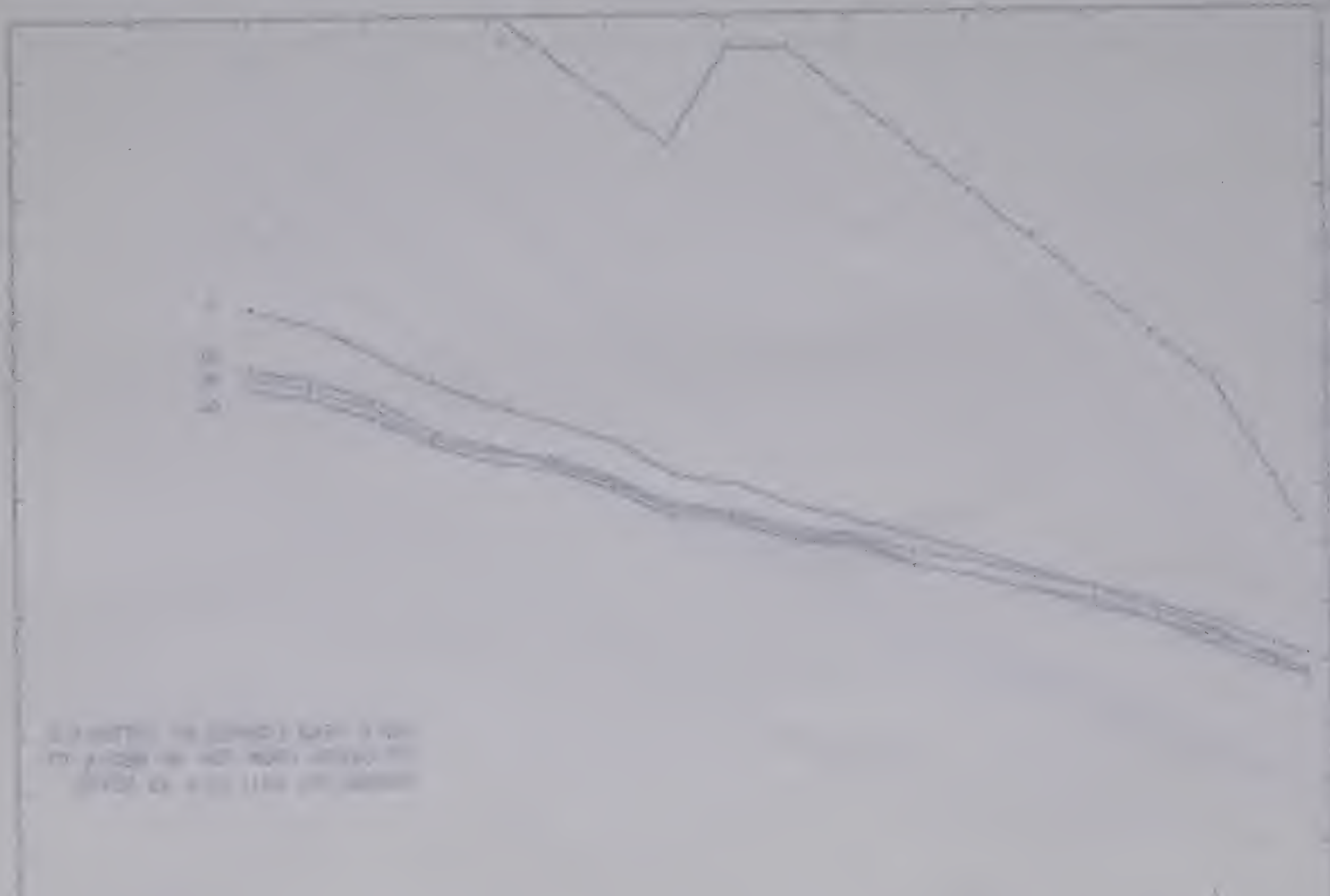


FIGURE 32: HEAD LOSS CURVES

COMPOSITE COKE 12.0 U.S.GPM/SQ.FT.



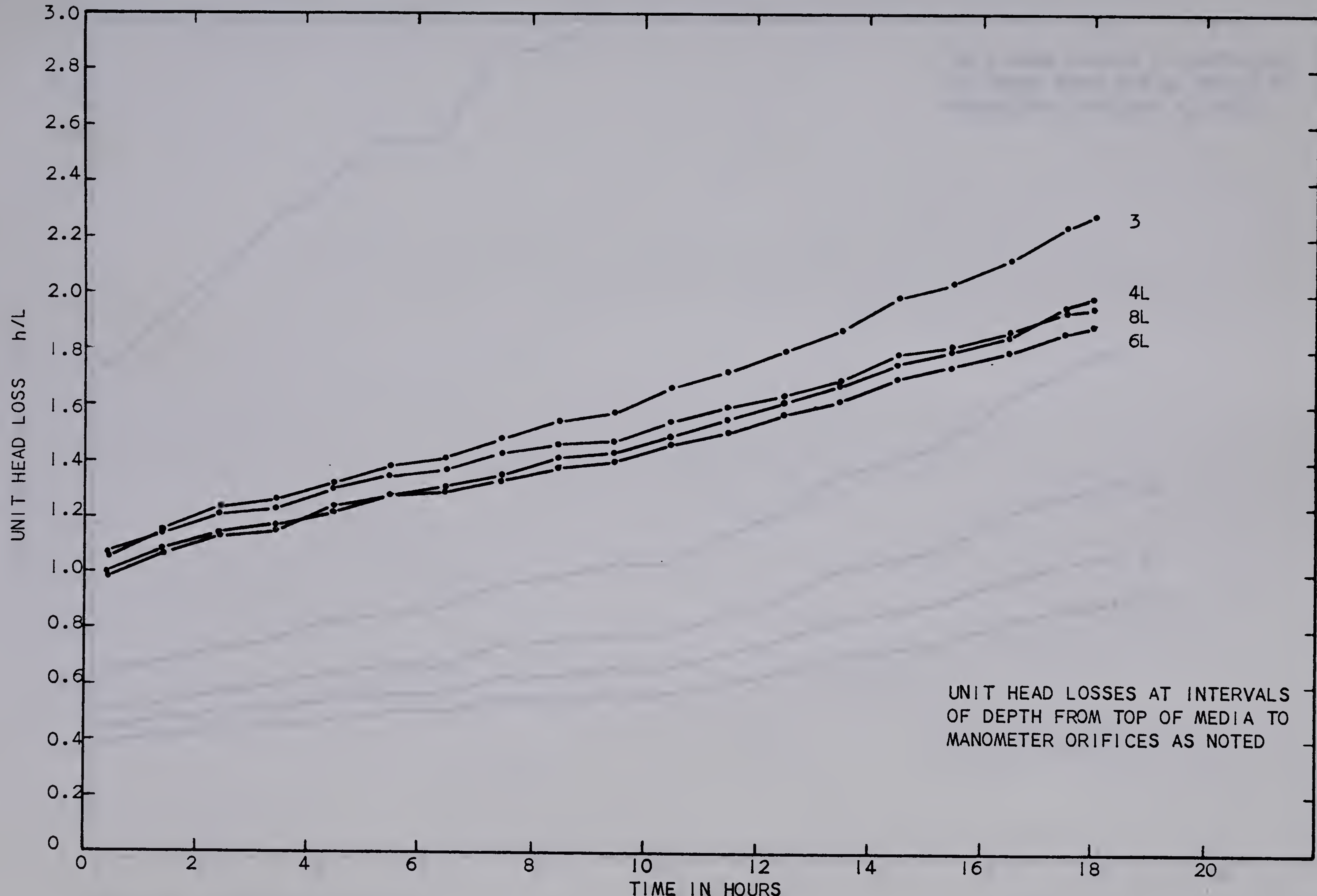


FIGURE 33: HEAD LOSS CURVES

COMPOSITE COKE 15.0 U.S.GPM/SQ.FT.

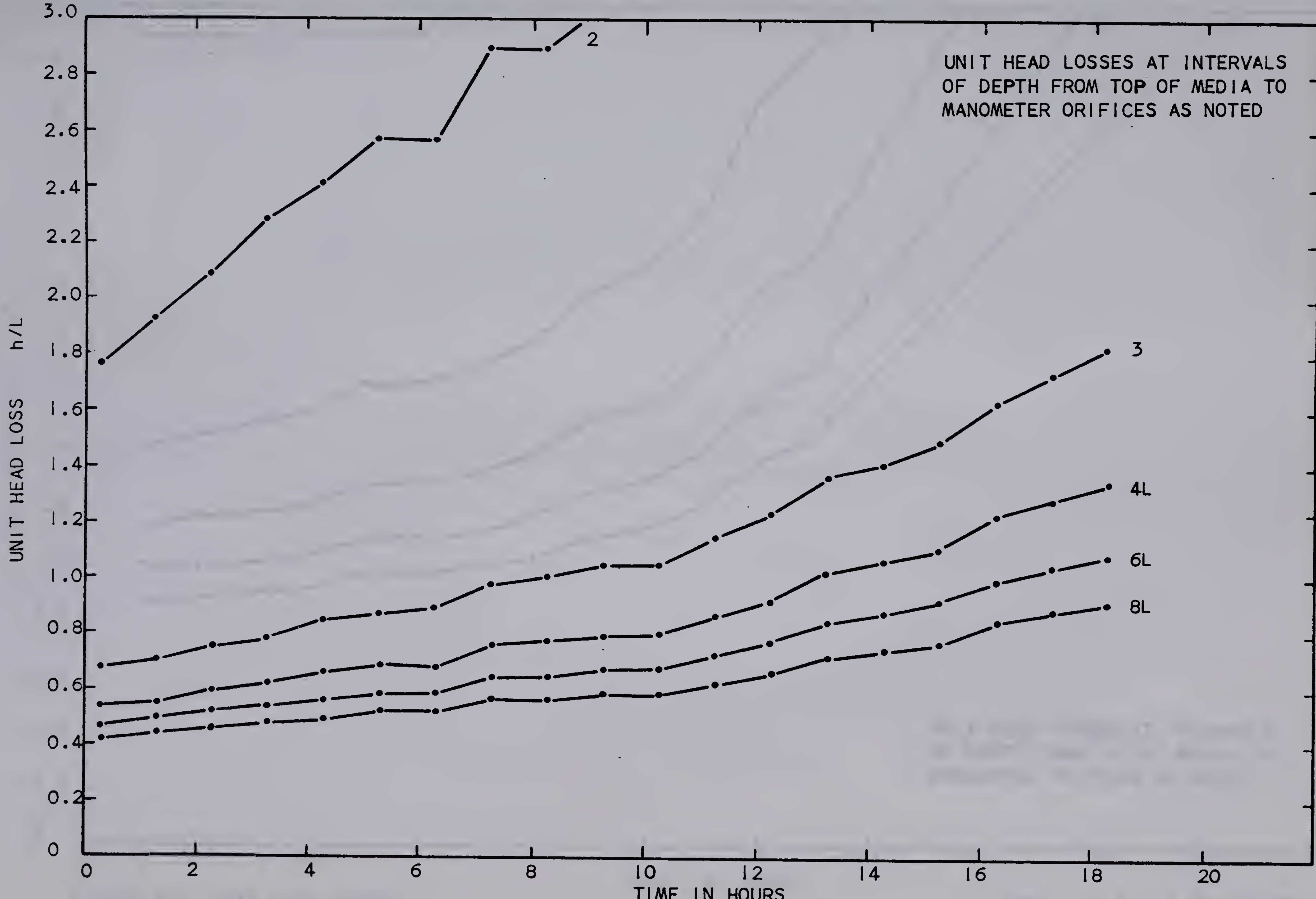


FIGURE 34: HEAD LOSS CURVES

SAND 2.4 U.S.GPM/SQ.FT.

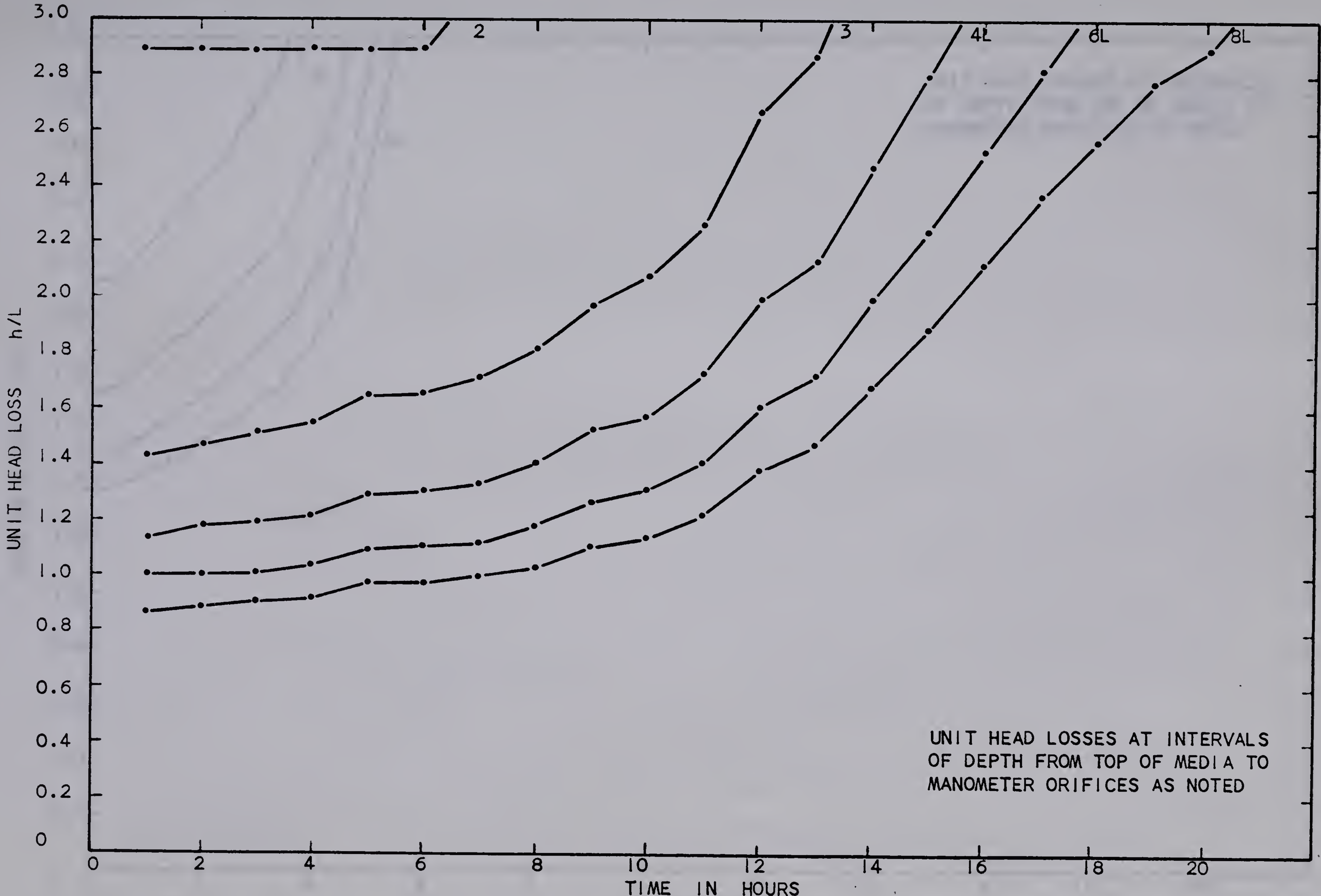


FIGURE 35: HEAD LOSS CURVES

SAND 5.0 U.S.GPM/SQ.FT.

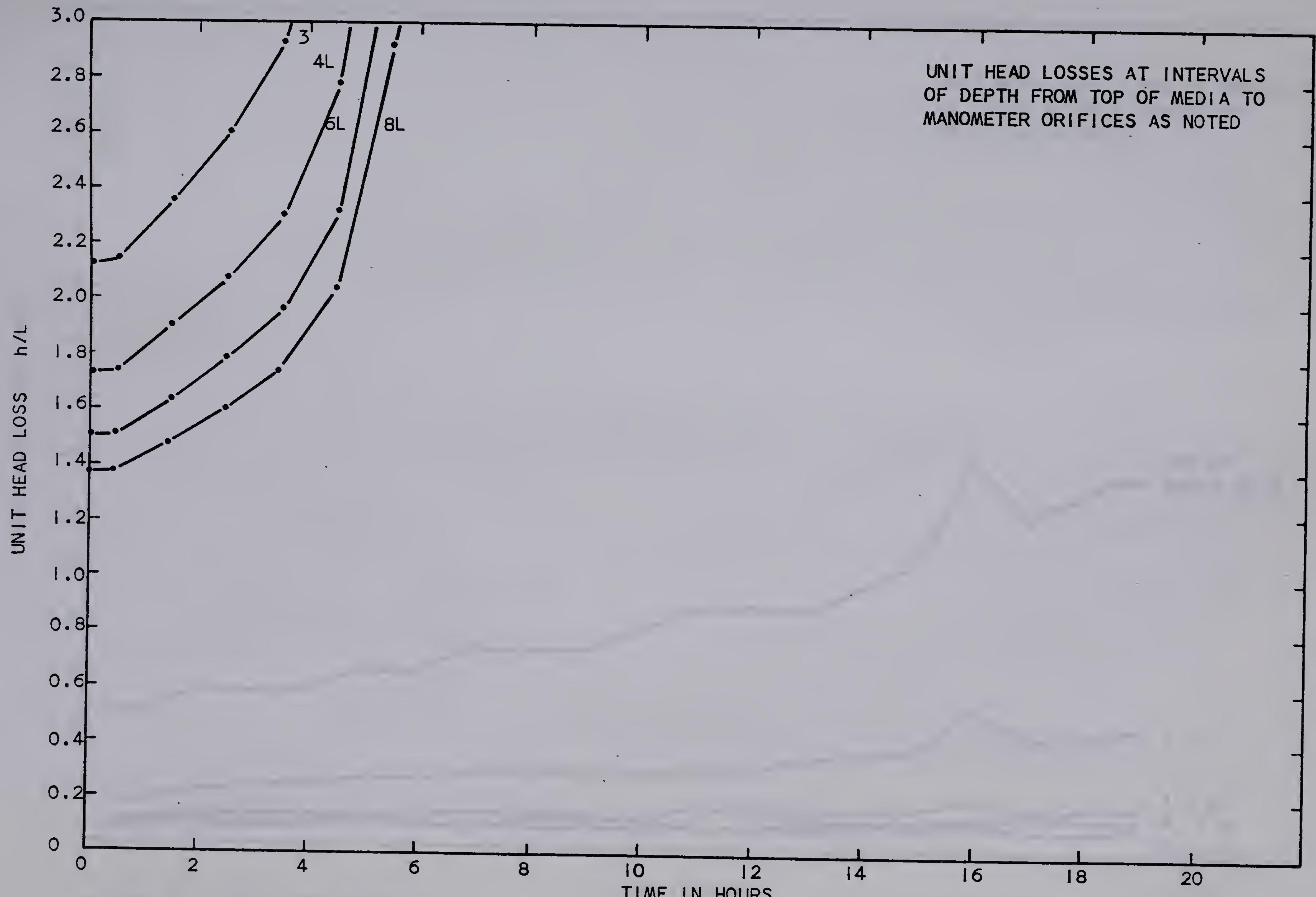


FIGURE 36: HEAD LOSS CURVES

SAND 8.5 U.S.GPM/SQ.FT.

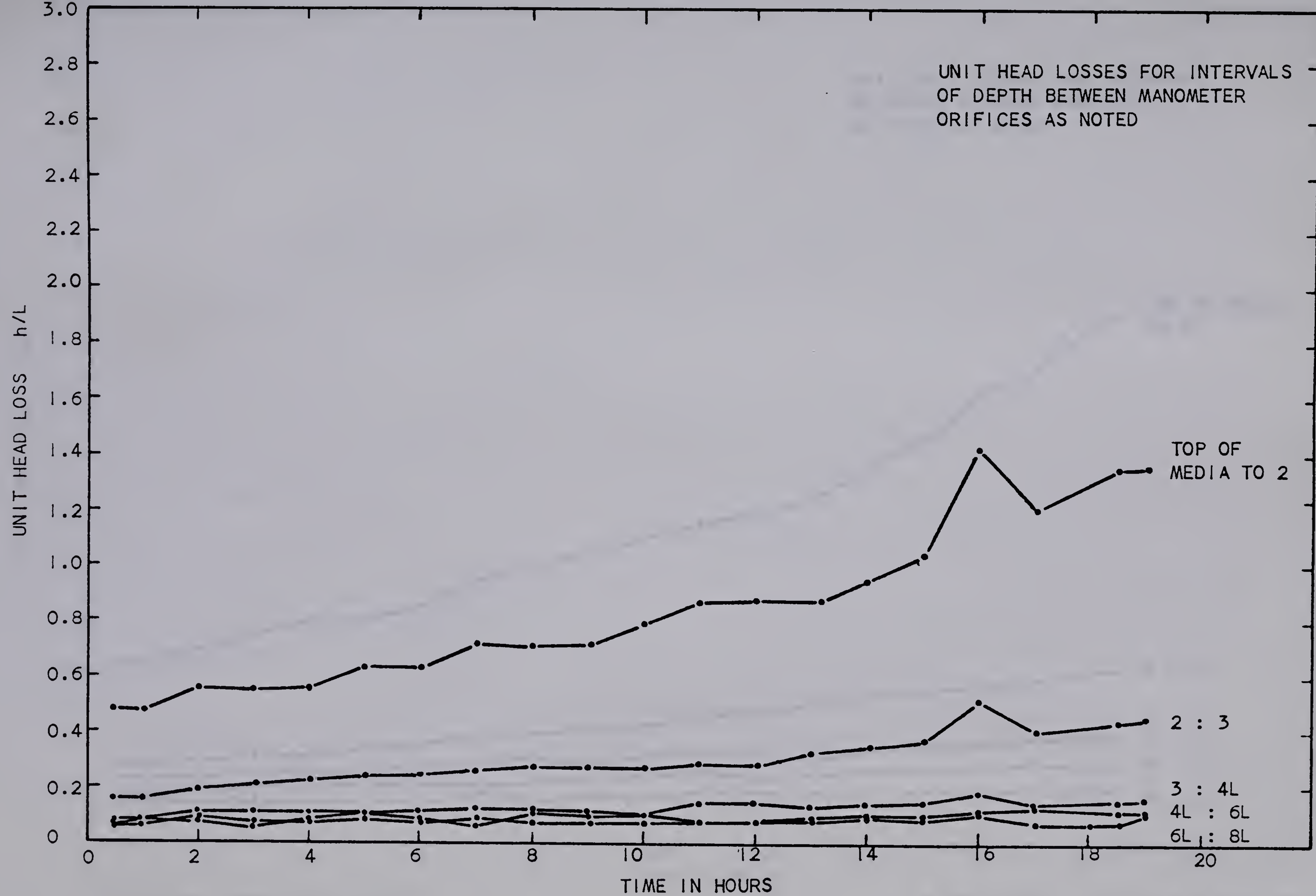


FIGURE 37: HEAD LOSS CURVES

MICHEL COKE 2.4 U.S.GPM/SQ.FT.

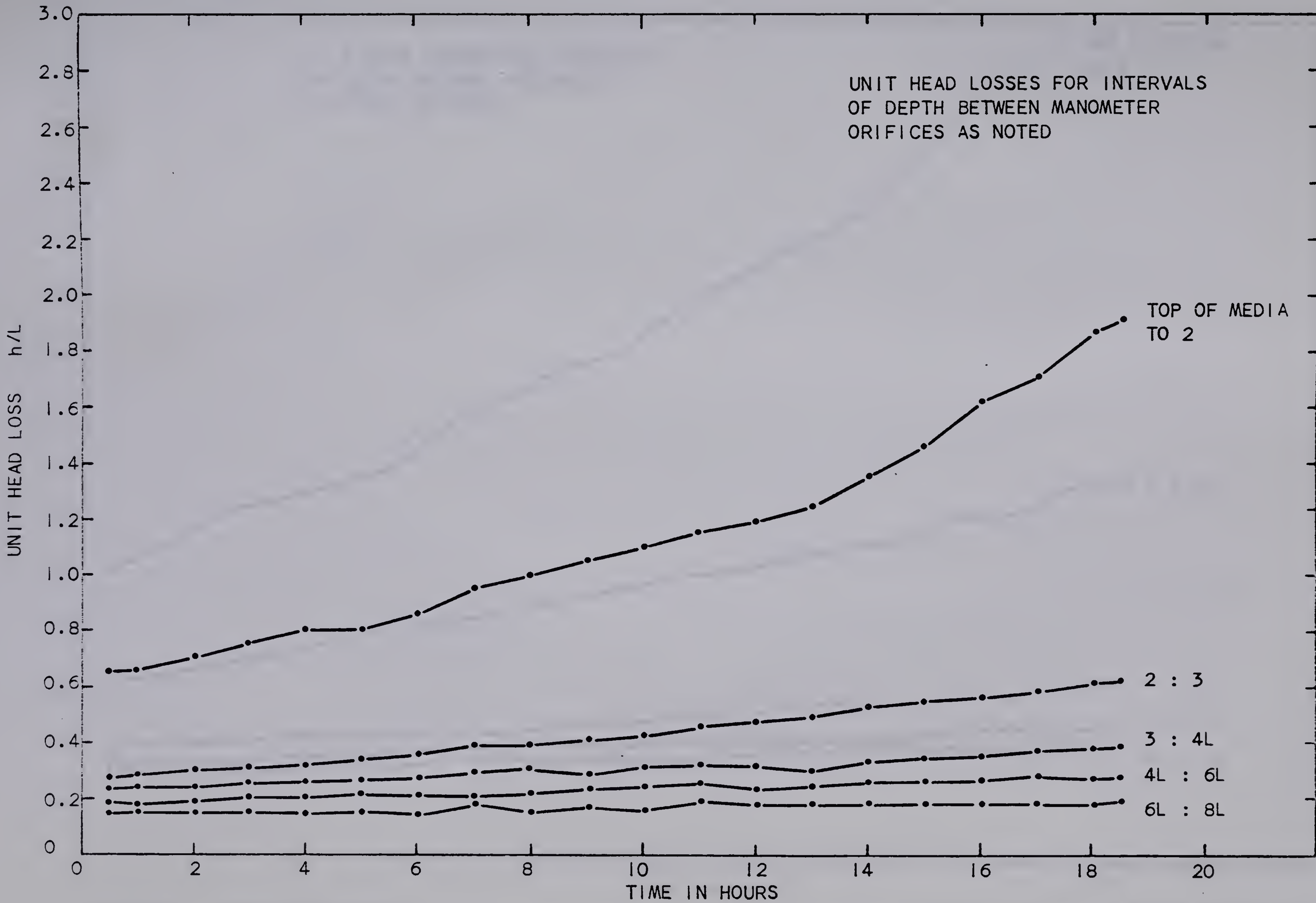


FIGURE 38: HEAD LOSS CURVES MICHEL COKE 5.0 U.S.GPM/SQ.FT.

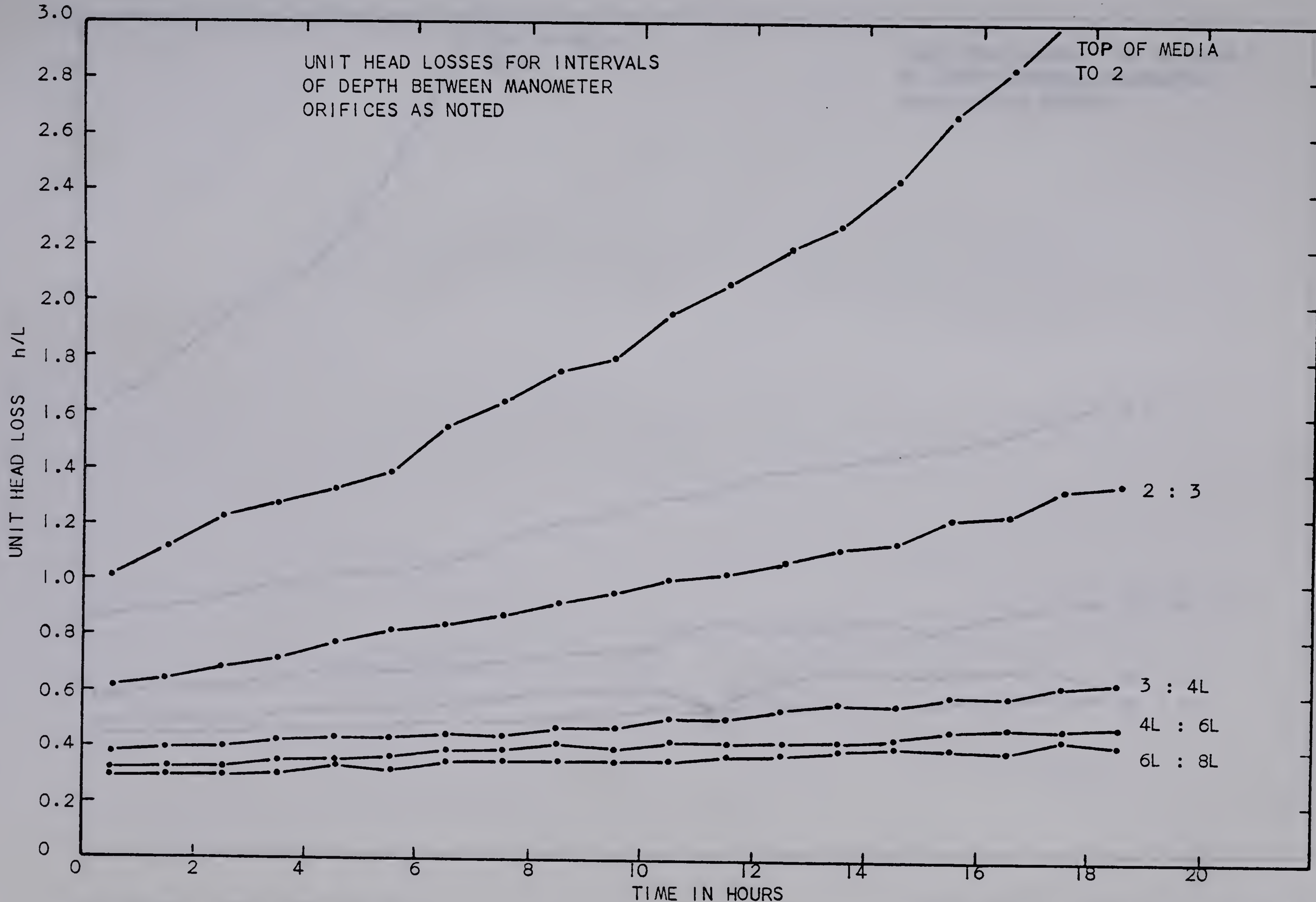
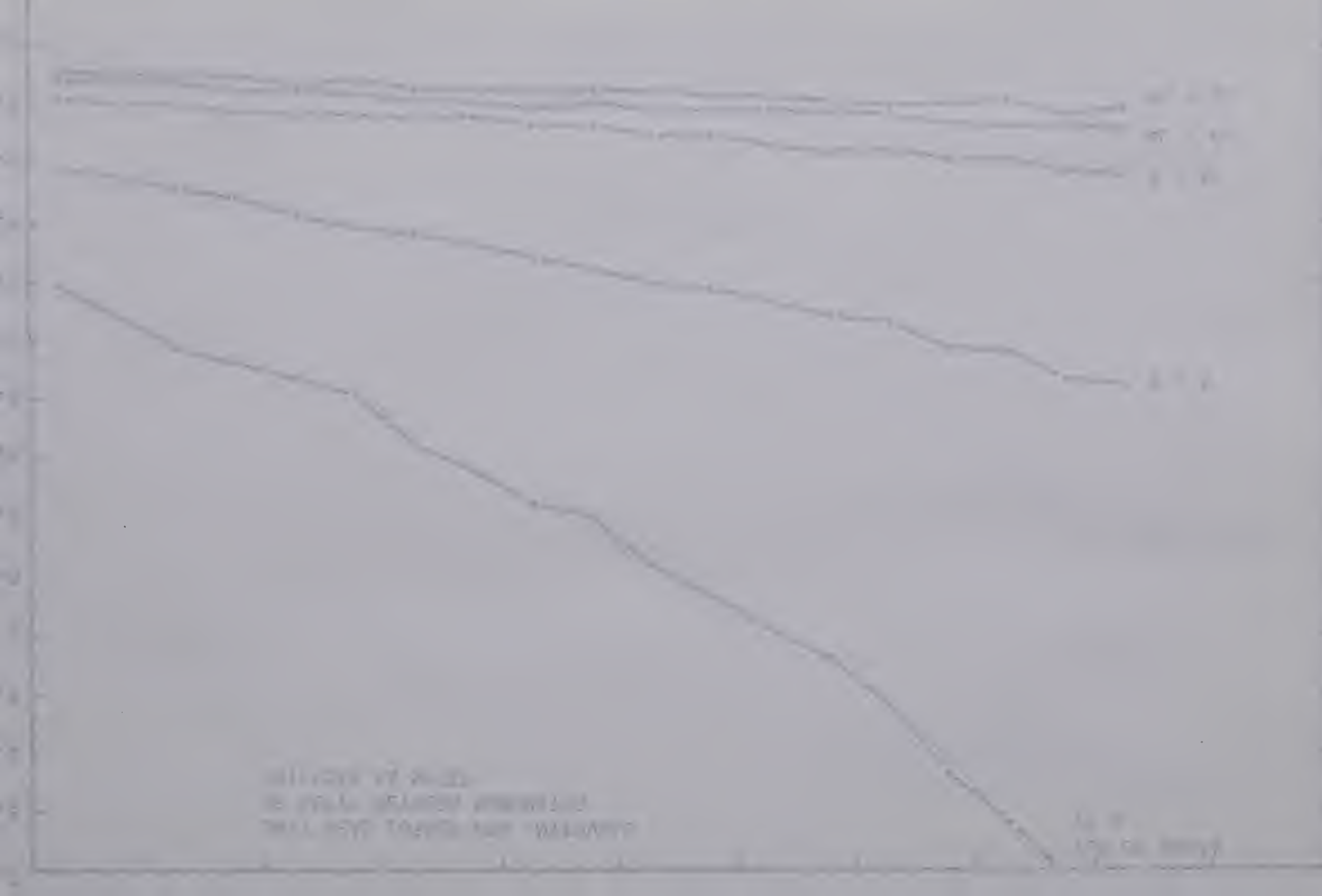


FIGURE 39: HEAD LOSS CURVES

MICHEL COKE 8.5 U.S.GPM/SQ.FT.



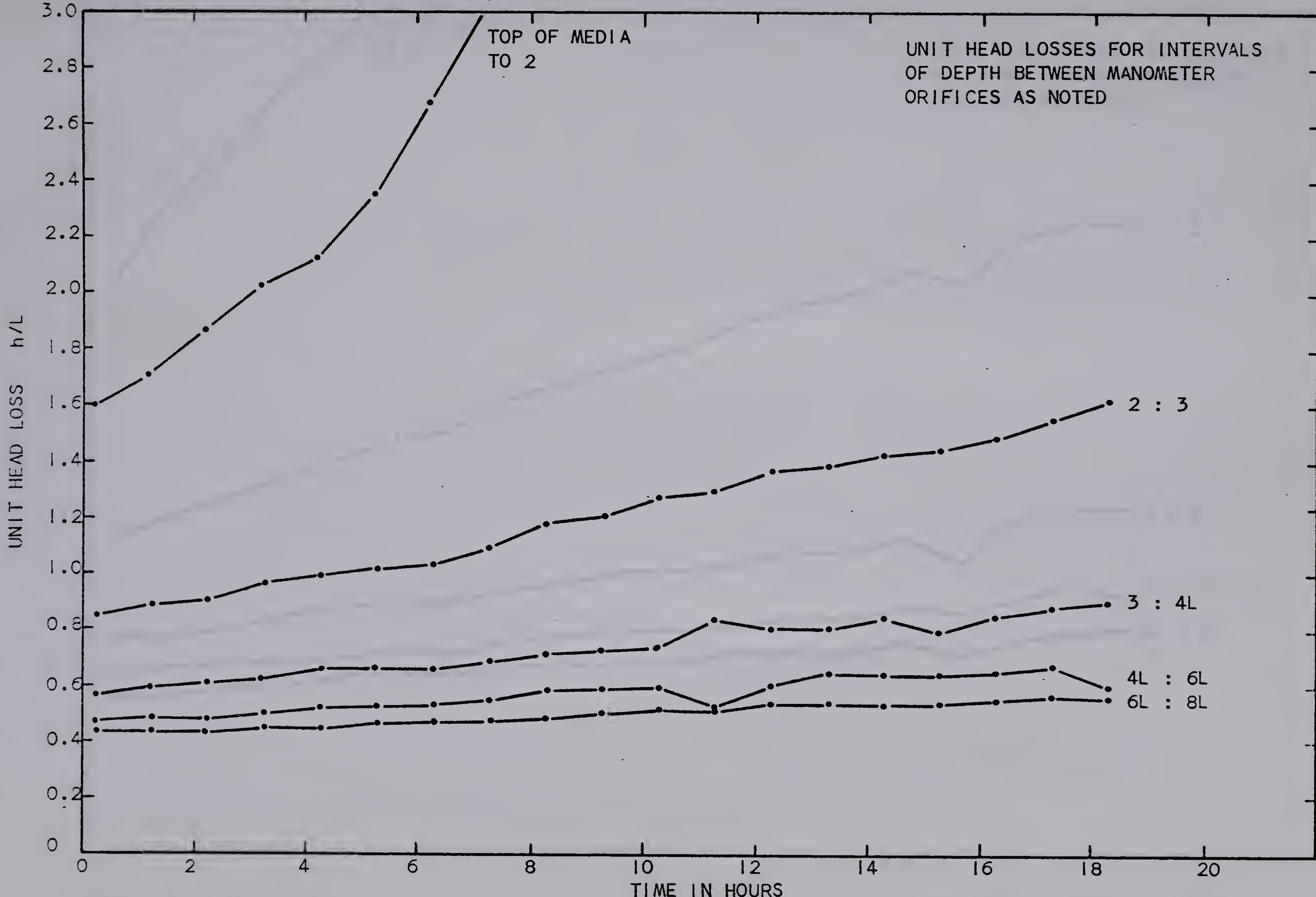


FIGURE 40: HEAD LOSS CURVES

MICHEL COKE 12.0 U.S.GPM/SQ.FT.

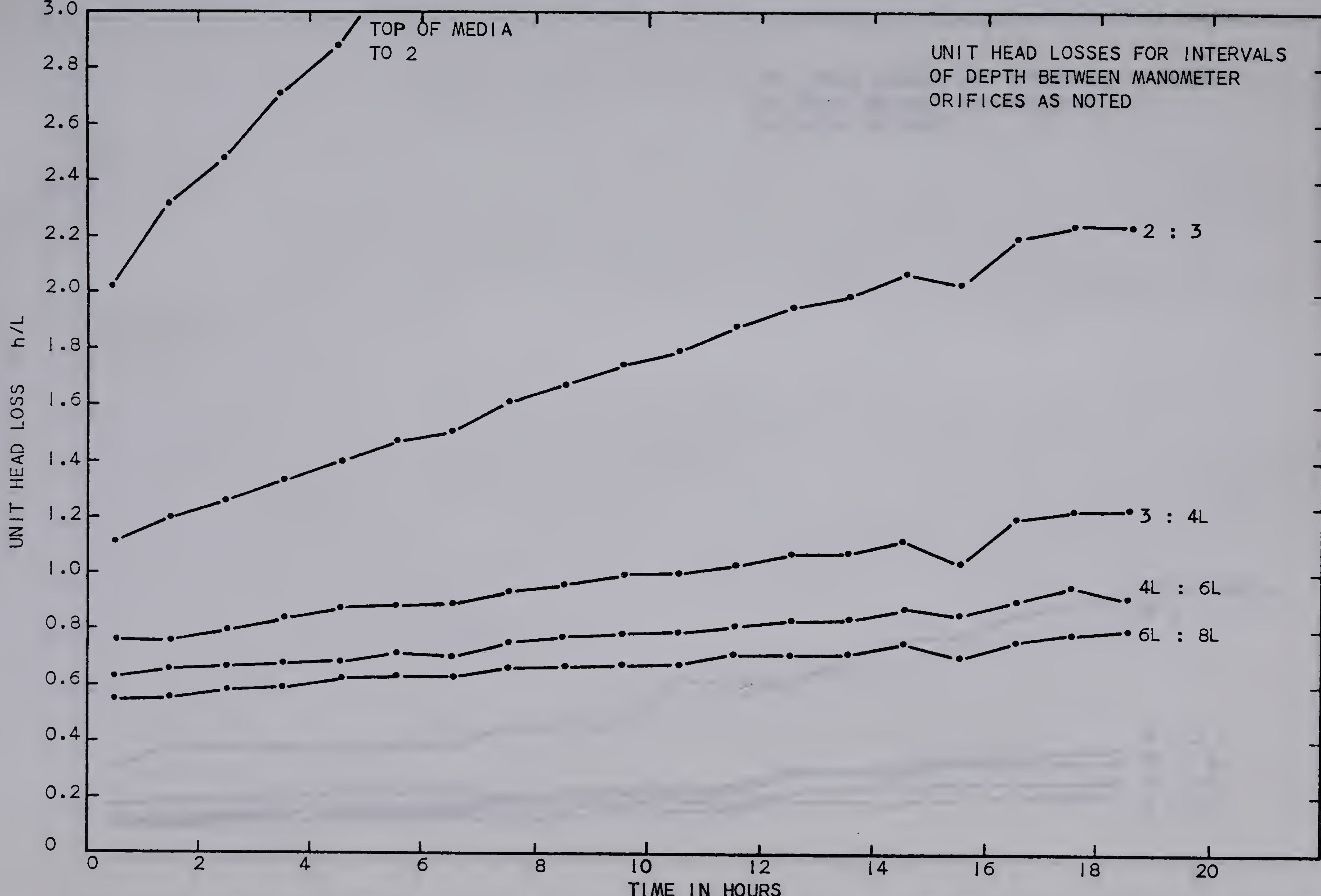


FIGURE 41: HEAD LOSS CURVES

MICHEL COKE 15.0 U.S.GPM/SQ.FT.

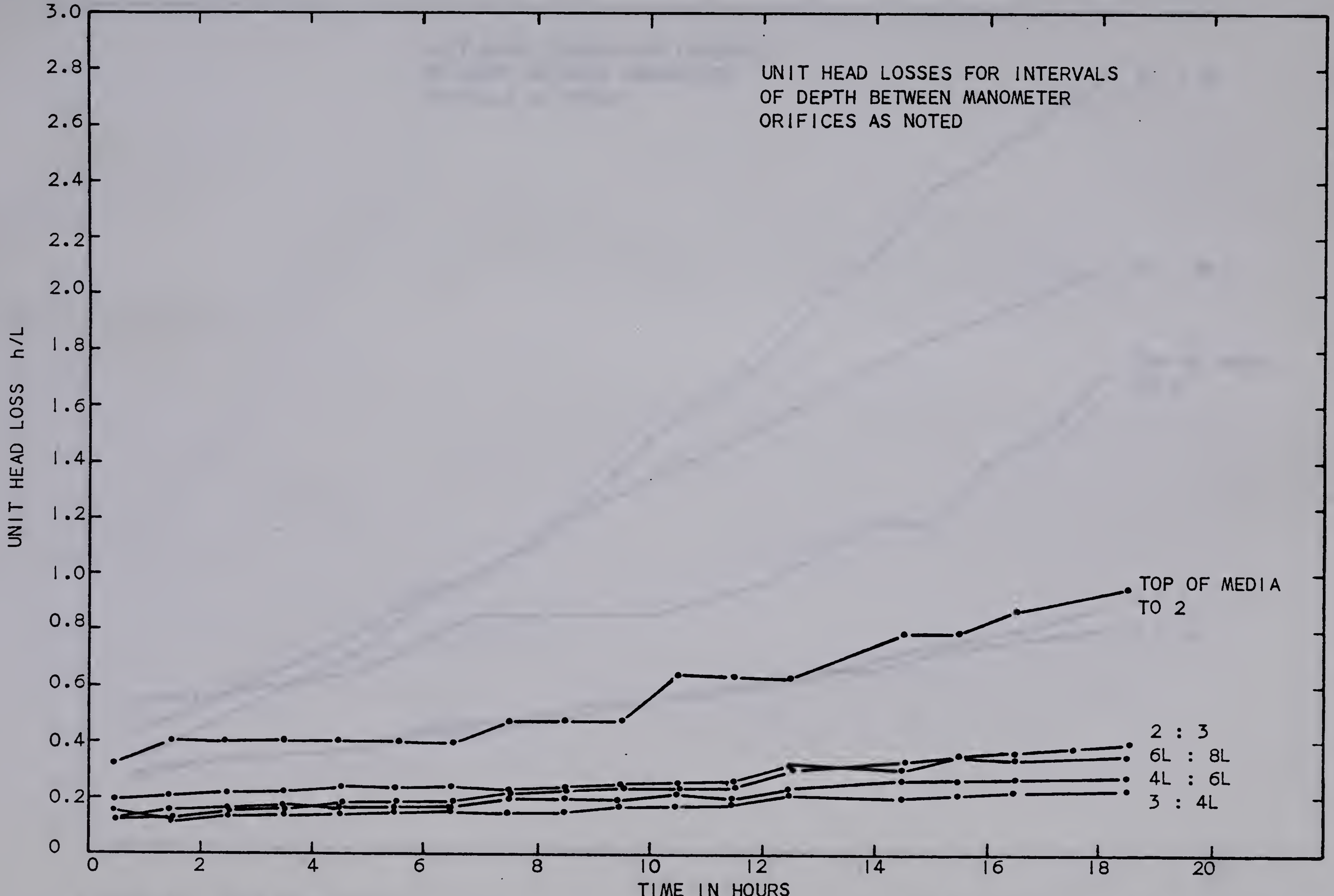


FIGURE 42: HEAD LOSS CURVES

COMPOSITE COKE 2.4 U.S.GPM/SQ.FT.

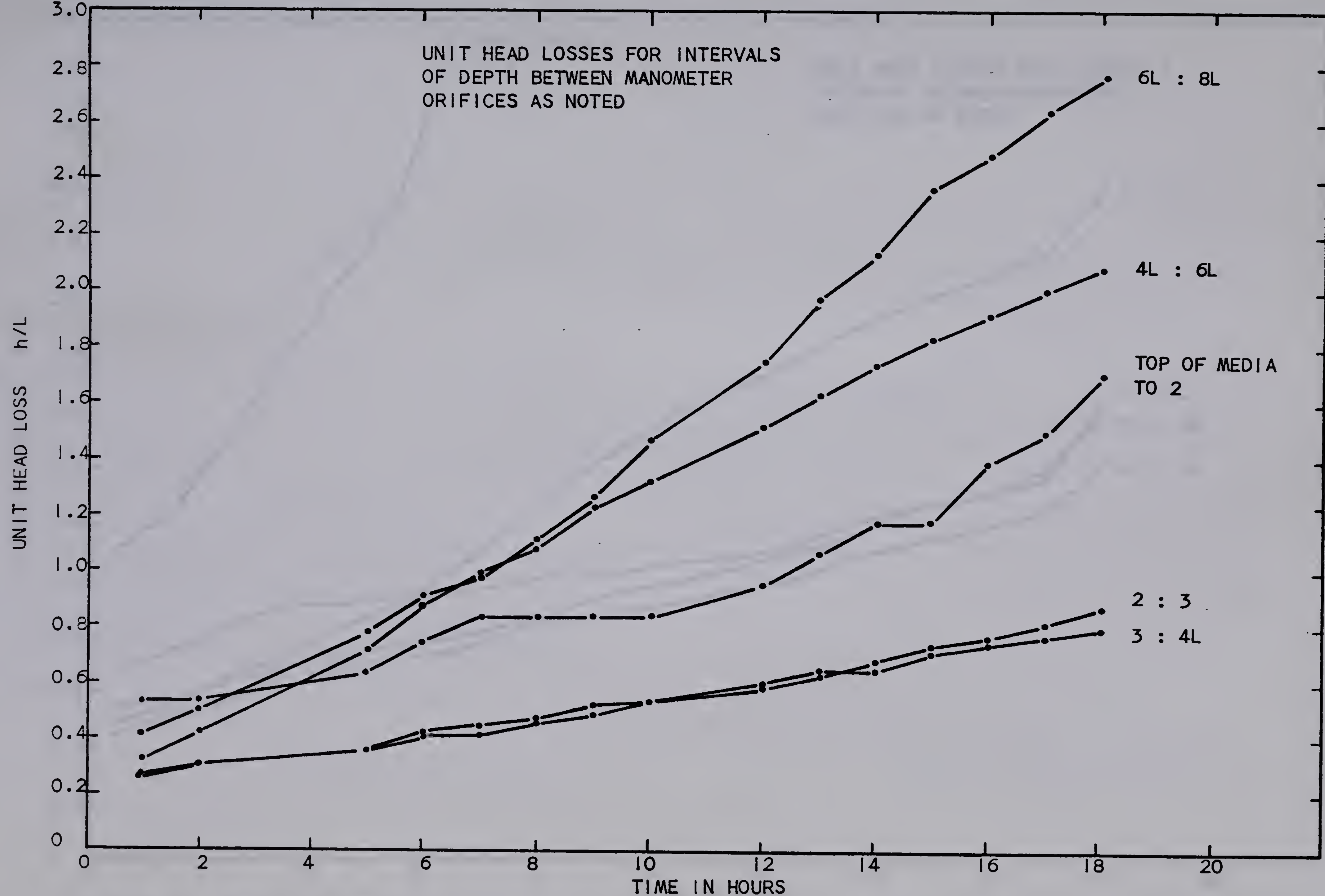


FIGURE 43: HEAD LOSS CURVES

COMPOSITE COKE 5.0 U.S.GPM/SQ.FT.

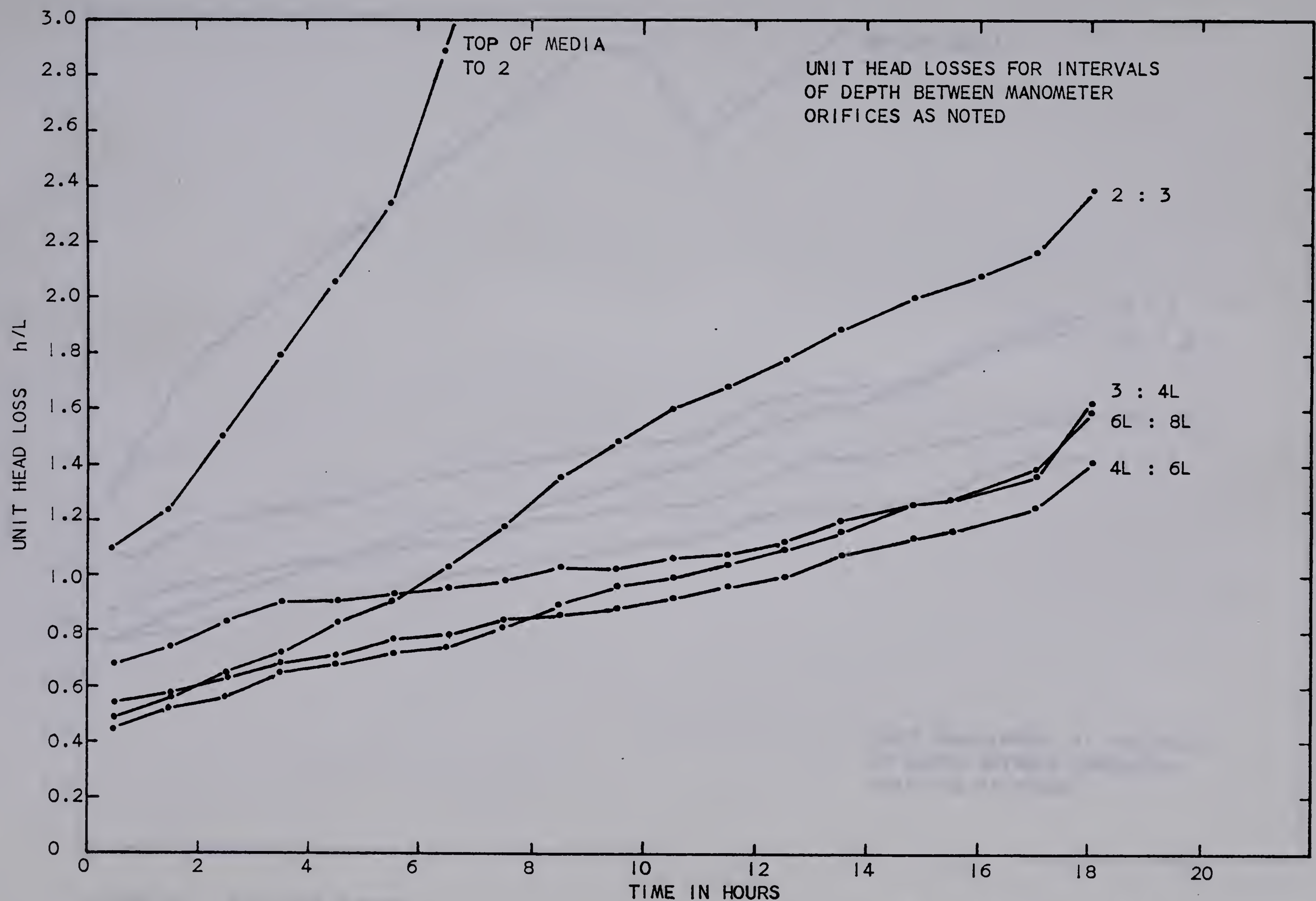


FIGURE 44: HEAD LOSS CURVES

COMPOSITE COKE 8.5 U.S.GPM/SQ.FT.

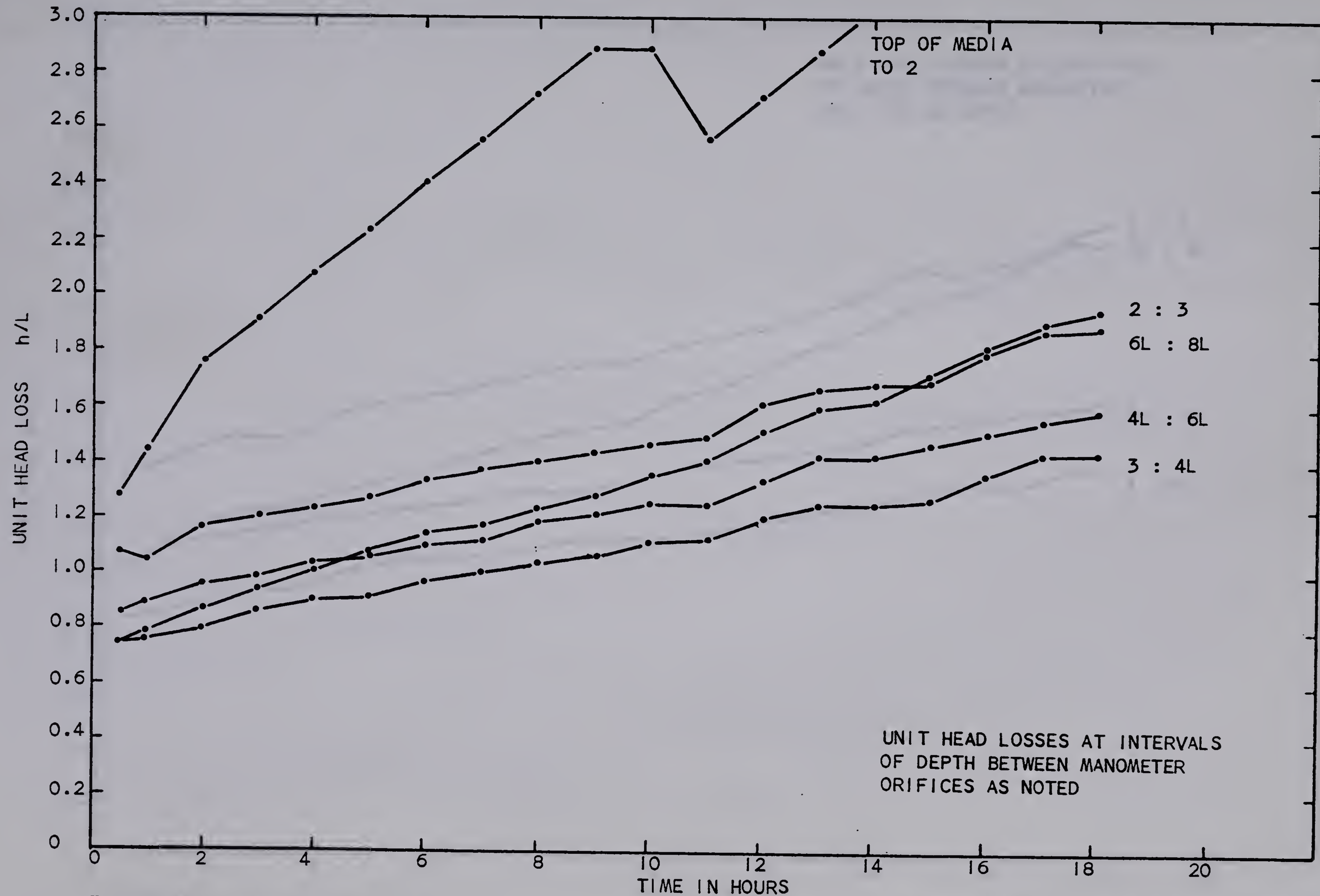


FIGURE 45: HEAD LOSS CURVES

COMPOSITE COKE 12.0 U.S.GPM/SQ.FT.

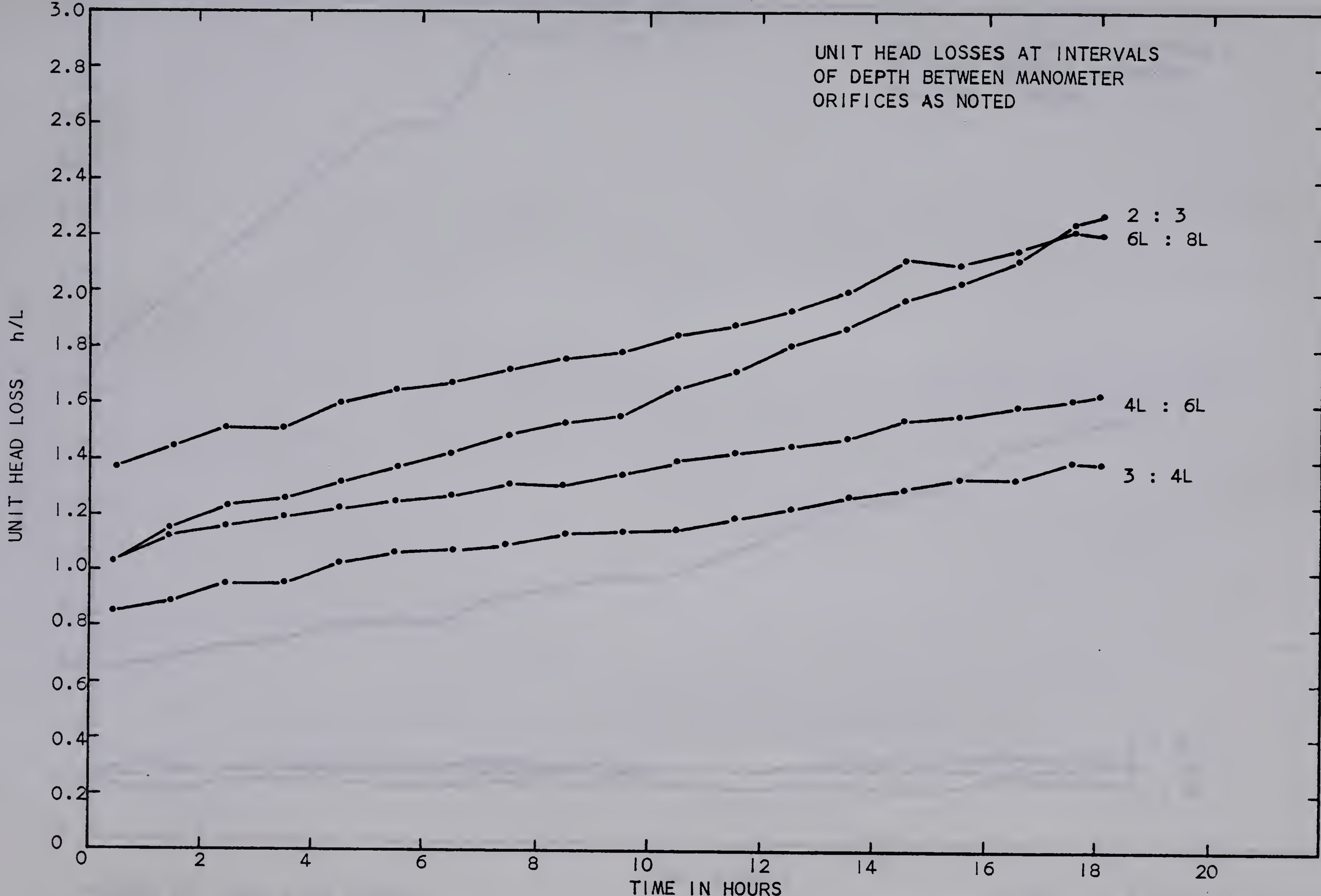


FIGURE 46: HEAD LOSS CURVES

COMPOSITE COKE 15.0 U.S.GPM/SQ.FT.

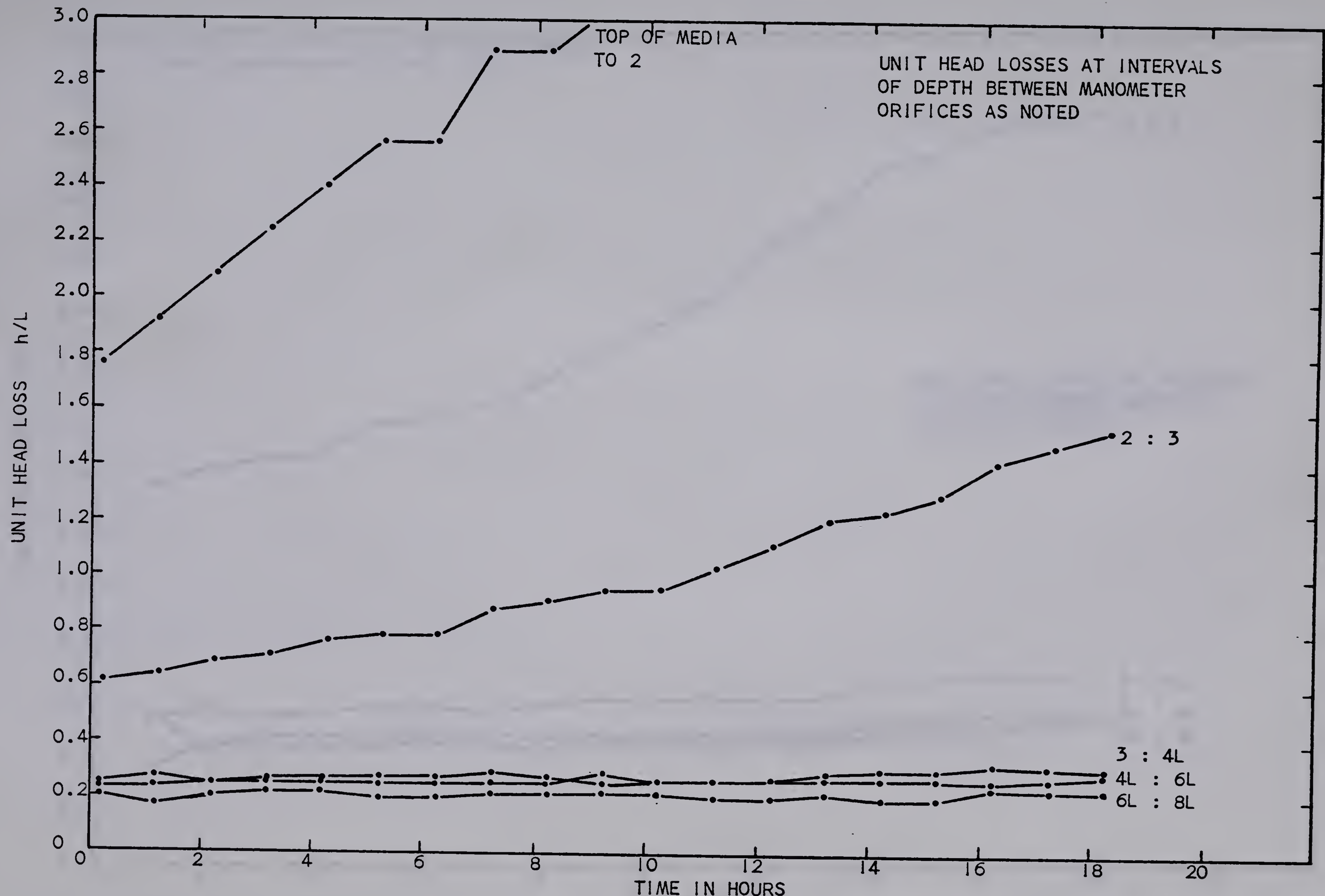


FIGURE 47: HEAD LOSS CURVES

SAND 2.4 U.S.GPM/SQ.FT.

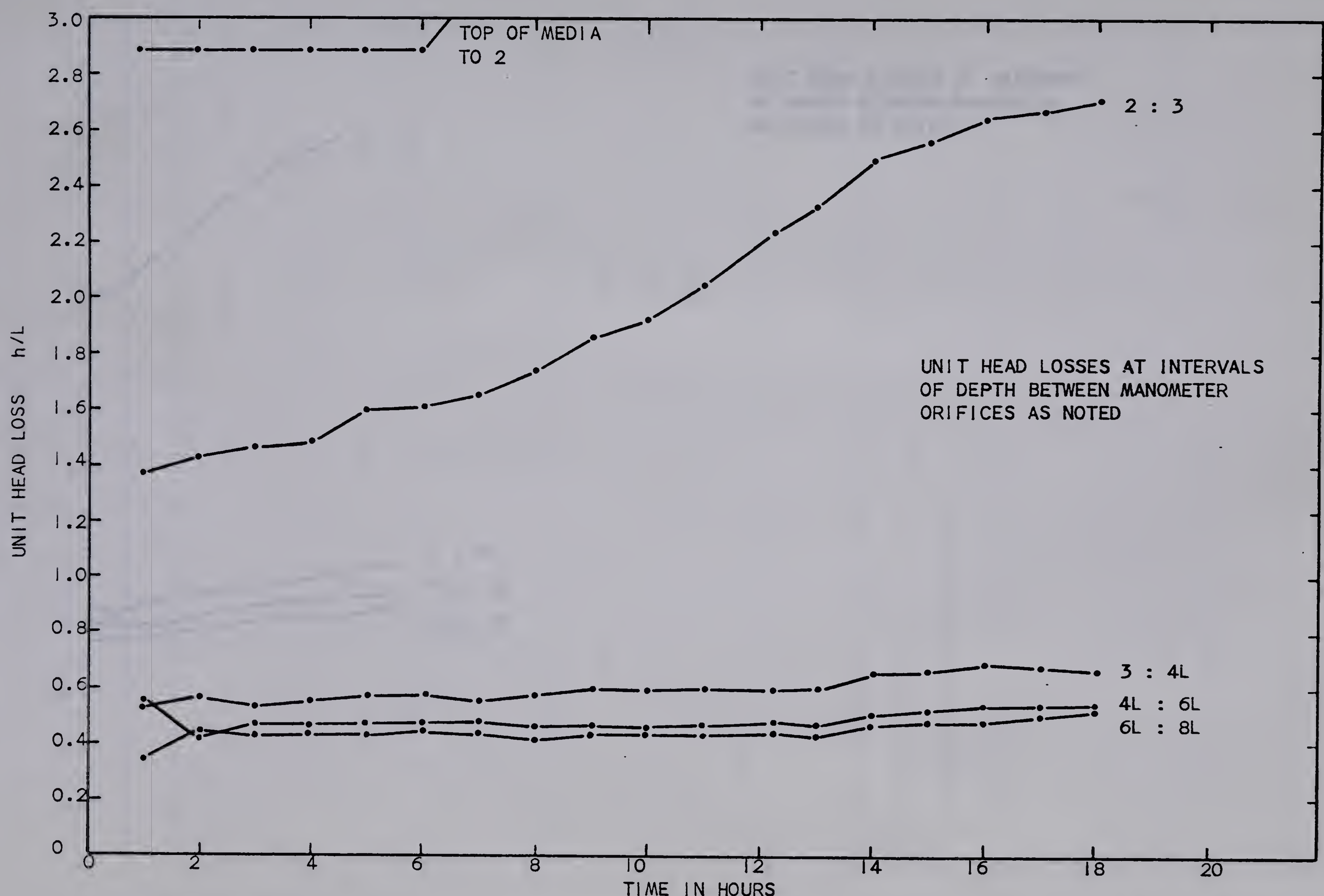


FIGURE 48: HEAD LOSS CURVES

SAND 5.0 U.S.GPM/SQ.FT.

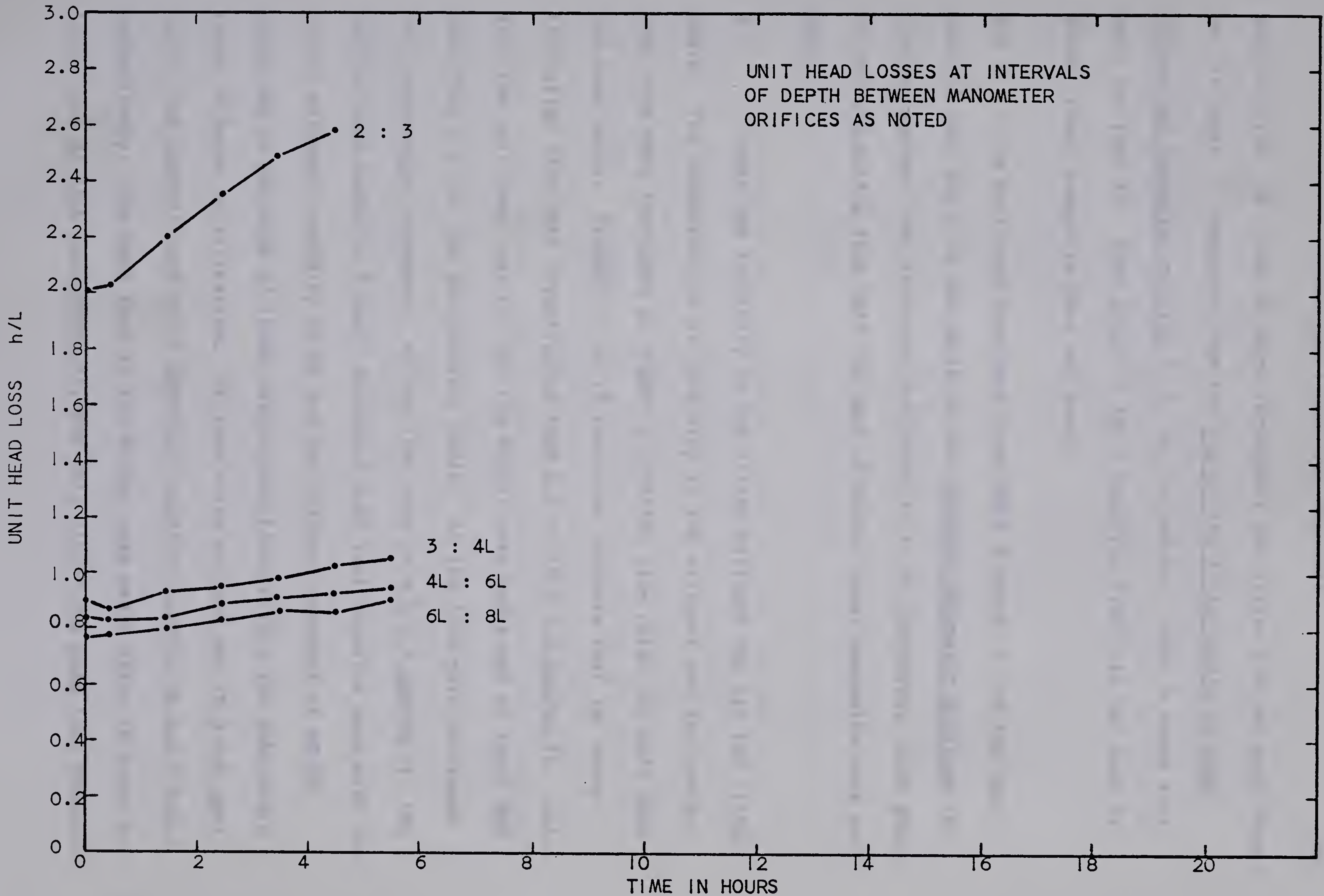


FIGURE 49: HEAD LOSS CURVES

SAND 8.5 U.S.GPM/SQ.FT.

each orifice vs time in hours throughout the filter run for each interval of depth L measured from the <u>top of the filter media to each respective manometer orifice</u> 2, 3, 4L, 6L and 8L. TABLE X shows this data for test 19. Each graph is for a specific flow rate for each of Michel coke, composite coke and sand.

4.6 The unit head loss data from TABLE X where h is the head loss in feet and L is the depth in feet <u>between manometer orifices</u> is plotted against time in hours in FIGURES 37 to 49 inclusive. Each graph is for a specific flow rate for each of Michel coke, composite coke and sand.

4.7 There was turbidity in the filter effluent for all the filter media. The concentration of turbidity in the effluent and the overall head loss were increased by higher filtration flow rates for both sand and coke media. FIGURES 11 to 15 inclusive indicate that for every filtration flow rate investigated from 2.4 to 15.0 U.S.gpm/sq.ft. inclusive the unit head loss h/L for the Michel coke media was at least 55% less than h/L for the sand control media. As the flow rate increased this percentage increased. At the flow rate of 8.5 U.S.gpm/sq.ft. the control sand media in 7 hours developed 0.93 feet negative head with the filter effluent turbidity 43.0% and the influent constant at 40.0%. There was no evidence of these severe conditions within the coke media after 18 hours of filtration. At flow rates of 12.0 and 15.0 U.S.gpm/sq.ft. the control sand media developed negative head in 5½ and 2 hours respectively. The head loss in the Michel coke media after 18 hours of filter run at 15.0 U.S.gpm/sq.ft. was only 51% of the head loss required

for negative head and for the composite coke media 43%. With reference to FIGURES 16 to 20 inclusive the filter performance for the sand media as related to effluent turbidity was equal to the Michel coke media at 2.4 U.S. gpm/sq.ft. At flow rates of 5.0, 8.5, 12.0 and 15.0 the Michel coke media maintained a higher quality of effluent with lower head losses. After 18 hours of filter run at 5.0 U.S. gpm/sq.ft., the effluent turbidity for sand was 58 ppm and for Michel coke 18 ppm. The head loss characteristics of Michel coke may be compared in more detail with the control sand media in FIGURES 24 to 28, 34 to 36, 37 to 41 and 47 to 49 inclusive for intervals of depth from the top of the filter media and intervals of depth between manometer orifices. Again the unit head losses are always higher for sand and the comparative values may be determined from the graphs for any specific combination of flow rate and depth interval. The Michel coke and control sand media had similar head loss characteristics for intervals of depth in that the unit head losses were highest at the top interval with the smallest grain size and became less as the grain size increased toward the lower intervals. This is in accordance with the hydraulics of sand filtration wherein h/L varies inversely as d^2 for laminar flow.

4.8 The head loss characteristics in the composite coke media (FIGURES 42 to 46 and 29 to 33 inclusive) wherein an attempt was made to reverse the stratification, did indicate this reversal was partly successful but there was not a consistent pattern throughout the various flow rates. The grain size and specific gravity design of the composite coke particles was based on discrete spherical grains in a quiescent fluid.

The coke grains of indeterminate diameter and very irregular in shape would have a high surface area-volume shape factor and tend to settle more slowly than spherical grains. The drag force is a function of the cross-sectional area of the grain relative to the direction of motion and this is constantly changing. The Reynolds numbers for the wash flow rates were of the order of 2.4 to 7.0 and would be approaching the condition wherein the irregular shape is affecting the drag. Thus it is believed the composite coke did not settle and stratify according to design and also that the stratification was not consistent after each filter wash. It was difficult to visually observe and verify this condition in the filter tube. However the graphs do indicate a higher unit head loss near the bottom layer of the filter bed where the smaller grains were expected to be, than in the intermediate layers. FIGURE 43 indicates for a flow rate of 5 U.S.gpm/sq.ft. the layer near the bottom of the filter media caused higher unit head losses than the top layer. FIGURE 17 for the same flow rate indicates a very high quality of effluent but FIGURE 12 indicates a higher overall head loss for composite coke as compared to Michel coke. Thus, when the composite coke media was removing turbidity more effectively than the Michel coke it was sustaining higher overall head losses.

4.9 In FIGURE 21 there is a straight-line relationship between flow rate and unit head loss up to about 8.5 U.S.gpm/sq.ft. for the various filter media. For laminar flow in filtration $\frac{h}{L}$ varies directly as the velocity. At flow rates of 12.0 and 15.0 U.S.gpm/sq.ft. the resultant curve is concave downward similar to a curve for h/L an exponential function of flow rate or velocity. In calculating Reynolds

number ($R = \frac{vd}{n}$) and using these values to check for limits of laminar flow from the graph of R vs C_d in Fair and Geyer (1954) the results were reasonably in agreement with the above, considering that in the stratified filter bed d varied from 0.352 to 1.288 millimeters.

4.10 The formula for the hydraulics of filtration from Fair and Geyer (1954) for head loss is $\frac{h}{L} = 0.178 \frac{v^2}{g} \frac{1}{e^4} \frac{a}{b} \sum \left(C_d \frac{P}{d} \right)$. This was checked for a flow rate of 8.5 U.S. gpm/sq.ft. from test 31 for sand and 24-A for Michel coke. The actual and theoretical values of $\frac{h}{L}$ for sand were 1.64 and 1.86 respectively. The shape factor $\frac{a}{b}$ is approximate and difficult to evaluate. A value of 5.5 from TABLE III (rounded sand grains) should be 4.8 to give a theoretical value of 1.64. For Michel coke $\frac{h}{L}$ was 0.45 actual value and would require a shape factor value of 1.5 for the formula to yield the actual value. However TABLE III indicates the shape factor may well be in excess of 6.0. The head loss varies inversely as the fourth power of the porosity. The higher porosity and surface area of the Michel coke media would contribute to the lower headlosses in coke than in sand media. It was not the purpose of this investigation to derive a formula for coke filtration or modify existing formulas based on sand media; however in the brief review of experimental versus theoretical data it was apparent that considerable study is required to determine diameter of coke grains relative to sieve sizes, the surface area-volume shape factors for coke and verification of its specific gravity. Grain size in a cellular material such as coke should be correlated with specific gravity.

4.11 In FIGURE 22 the varying head loss (concave upward curves) for sand and Michel coke shows the grading in these filter media from fine grains in the top layer to coarse grains at the bottom. The approximate straight lines for composite coke show the reverse stratification was achieved in part.

4.12 The data on filter washing plotted on FIGURE 23 as percent expansion vs U.S.gpm/sq.ft. indicates the coke media requires approximately 50% lower wash water flow rate for 40% expansion of the media. With a specific gravity of 1.83 for Michel coke as compared to 2.65 for sand the effective weight in water of coke grains of equivalent sieve size to sand is less, requiring a lower drag force and subsequently lower wash water velocity to suspend the grains. In the filter washing tests the coke was observed to wash clean as readily as the sand.

4.13 Unlike sand grains the coke grains are porous, however it can reasonably be assumed that many pores will be completely enclosed or partly enclosed so that most fluids cannot penetrate. In determining the specific gravity of coke grains (paragraph 3.2) the derived value approaches the true value of coke solids as the volume of pore space within the grains not penetrated by the water decreases. Thus it was consistent to use the derived value of specific gravity of 1.83 for Michel coke to compute the porosity of this filter media (paragraph 3.4), for the effective void volume of the media should be considered to be the space between the grains. The pores in the grains would probably not conduct the flow of water but may affect the manner of flow and the process of filtration. The computed values of porosity for sand and

Michel coke was 0.40 and 0.70 respectively. Test 28 was a secondary test for porosity. The filter tube was drained down to the level of the top of the filter media. The volume of water drained off from this point to a lower point in the filter was measured and the total volume of the filter tube between the same points was calculated. This porosity value was 0.58 for Michel coke and 0.36 for sand. These lower values in Test 28 would be for the greater part due to the film of water remaining on the grains and between the grains that did not drain away completely into the measuring cylinder.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 On a qualitative basis and within the limits of this investigation Michel coke is a suitable filter media for the following reasons:

1. It was readily crushed and sieved to the required size and grading.
2. In the model filter it was easily wetted and put into filter service.
3. The filtering process was normal with the turbidity concentrating on top of the media and in the top layer moving progressively down through the media throughout the filter run.
4. The coke was expanded easily in a normal manner during the filter washing process and no caking occurred.
5. Turbidity was easily washed from coke grains and there was no permanent discoloration of the grains.
6. Stratification after filter washing was observed to be normal.
7. The coke was a durable media with respect to both the filtering and washing process.

5.2 In the filtration tests the unit head loss for the Michel coke media was at least 55% less than the control sand media for all flow rates investigated. This percentage increased as the flow rate increased. The sand control media could not sustain flow rates of 8.5, 12.0 and 15.0 U.S.gpm/sq.ft. with an influent turbidity of 100 ppm without developing negative head within 7, 5½ and 2 hours respectively. The coke media easily sustained 18 hours of filtration with the maximum head loss only

43% of that required for negative head. The quality of filter effluent was higher for Michel coke media with 18% of the 100 ppm turbidity passing through after 18 hours at 5.0 U.S.gpm/sq.ft. while the control sand media was passing 54% of the turbidity. The composite coke media removed the turbidity more effectively than Michel coke media but sustained higher overall head losses; however both coke media were more efficient than the control sand media.

5.3 In the filter washing tests the coke media required approximately 50% lower wash water flow rate for 40% expansion of the media as compared to the control sand media. This reduces the volume of water required for filter washing by 50%.

5.4 It is recommended that the investigation be advanced to include the coke rapid filter model in a complete water treatment process with coagulation, sedimentation and filtration. The hydraulics of filtration in coke media would be an interesting pursuit, for the coke of the same sieve size and grading as the sand media had the desirable characteristics of storing more turbidity within the media and sustaining much lower head losses. Further study of coke grains should be made relative to surface area-volume ratios, surface activity, volume of cell space, correlation between specific gravity and grain size and sieve size-diameter relationship.

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